Search for Resonant and Nonresonant Higgs Boson Pair Production in the $b\bar{b}\tau^+\tau^-$ Decay Channel in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

M. Aaboud *et al.*[*]
(ATLAS Collaboration)

(Received 2 August 2018; published 7 November 2018)

A search for resonant and nonresonant pair production of Higgs bosons in the $b\bar{b}\tau^+\tau^-$ final state is presented. The search uses 36.1 fb^{-1} of pp collision data with $\sqrt{s} = 13$ TeV recorded by the ATLAS experiment at the LHC in 2015 and 2016. Decays of the τ-lepton pairs with at least one τ lepton decaying to final states with hadrons and a neutrino are considered. No significant excess above the expected background is observed in the data. The cross-section times branching ratio for nonresonant Higgs boson pair production is constrained to be less than 30.9 fb, 12.7 times the standard model expectation, at 95% confidence level. The data are also analyzed to probe resonant Higgs boson pair production, constraining a model with an extended Higgs sector based on two doublets and a Randall-Sundrum bulk graviton model. Upper limits are placed on the resonant Higgs boson pair production cross-section times branching ratio, excluding resonances X in the mass range 305 GeV $< m_X <$ 402 GeV in the simplified hMSSM minimal supersymmetric model for $\tan\beta = 2$ and excluding bulk Randall-Sundrum gravitons G_{KK} in the mass range 325 GeV $< m_{G_{\mathrm{KK}}} <$ 885 GeV for $k/\bar{M}_{\mathrm{Pl}} = 1$.

DOI: 10.1103/PhysRevLett.121.191801

In 2012, the ATLAS and CMS Collaborations at the LHC discovered a new particle with a mass of approximately 125 GeV [1–3]. According to all current measurements it is compatible with the standard model (SM) Higgs boson (H) [4–8]. An important pending test of the Brout-Englert-Higgs mechanism is the measurement of Higgs boson pair production. At the LHC, pairs of SM Higgs bosons can be produced via the Higgs self-interaction ("triangle diagram") and the destructively interfering top-quark loop ("box diagram") [9,10]. Nonresonant Higgs boson pair production (NR HH) can be significantly enhanced relative to the SM prediction by modifications to the top-quark Yukawa coupling, the trilinear Higgs boson coupling λ_{HHH}, or by introducing production mechanisms with new intermediate particles. Many theories beyond the SM predict heavy resonances that could decay into a pair of SM Higgs bosons, such as a heavy CP-even scalar X in two-Higgs-doublet models [11], or spin-2 Kaluza-Klein (KK) excitations of the graviton, G_{KK}, in the bulk Randall-Sundrum (RS) model [12–14].

This Letter describes a search for resonant and nonresonant Higgs boson pair production in a final state with two b quarks and two τ leptons using 36.1 fb^{-1} of pp collision data recorded with the ATLAS detector [15,16] in 2015 and 2016. The $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ and $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ decay channels are considered, where the subscripts (lep = electron or muon, had = hadrons) indicate the decay mode of the τ lepton. Previous searches for Higgs boson pair production were performed at center-of-mass energies $\sqrt{s} = 8$ TeV [17–19] and $\sqrt{s} = 13$ TeV [20–22] by the ATLAS and CMS Collaborations. The ATLAS search in the $4b$ channel constitutes the most sensitive result to date and the observed (expected) limit excludes a cross section greater than 13.0 (20.7) times the SM prediction at 95% confidence level (C.L.).

The SM nonresonant HH process was simulated with MadGraph5_aMC@NLO at next-to-leading order (NLO) [23–27] using the CT10 parton distribution function (PDF) set [28]. Parton showers and hadronization were simulated with Herwig++ [29] using the UEEE5 set of tuned parameters (tune) [30]. The events were reweighted to reproduce the m_{HH} spectrum obtained in Refs. [9,31], which fully accounts for the finite mass of the top quark. The cross-section times branching ratio to the $bb\tau\tau$ final state, evaluated at next-to-next-to-leading order (NNLO) and including next-to-next-to-leading logarithm (NNLL) corrections and NLO top-quark mass effects, is $2.44^{+0.18}_{-0.22}$ fb [32]. Events with a generic narrow-width scalar X or G_{KK} decaying into HH were produced in MadGraph5_aMC@NLO at leading order (LO) and interfaced to the Pythia 8 [33] parton shower model using the A14 tune [34] together with the NNPDF23LO PDF set [35]. The cross section and width of the G_{KK} were taken from Ref. [36] and

[*]Full author list given at the end of the article.

depend on $k/\bar{M}_{\rm Pl}$, where k corresponds to the curvature of the warped extra dimension and $\bar{M}_{\rm Pl} = 2.4 \times 10^{18}$ GeV is the effective four-dimensional Planck scale. Events with $k/\bar{M}_{\rm Pl} = 1$ and $k/\bar{M}_{\rm Pl} = 2$ were simulated.

The dominant SM background processes are $t\bar{t}$, QCD multijet and Z bosons produced in association with jets originating from heavy-flavor quarks (bb, bc, cc), subsequently referred to as $Z +$ heavy flavor [37]. SM Higgs boson production in association with a Z boson, subsequently decaying into a $bb\tau\tau$ [38] final state, is an irreducible background in this analysis. The $t\bar{t}$ and single-top-quark background events were simulated using POWHEG-BOX [39], with the CT10 PDF set, and MADSPIN [40]. The parton showers were simulated using PYTHIA 6 [41] and the Perugia 2012 tune [42]. The $t\bar{t}$ background was scaled to match the NNLO + NNLL cross sections [43], while the single-top samples were corrected to NLO [44,45] (approximate NNLO [46]) predictions for the t- and s-channel (Wt final state). Events with W or Z bosons and associated jets were simulated with the SHERPA 2.2.1 generator [47–51], using the NNPDF30NNLO PDF set [52] and normalized to the NNLO cross sections [53]. Diboson and Drell–Yan backgrounds were produced with SHERPA 2.2.1 [47] using the CT10NLO PDF set and the generator cross-section predictions. Quark-induced ZH processes were generated with PYTHIA 8, using the A14 tune and the NNPDF23LO PDF set. The samples were normalized to NNLO cross sections for QCD and NLO for electroweak processes [54–60]. The gluon-induced ZH process [61] was generated with POWHEG using the CT10 PDF set and using PYTHIA 8 with the AZNLO tune [62] to simulate parton showers. Cross sections [63–67] were scaled to NLO + NLL in QCD. SM Higgs boson production in association with a top-quark pair was simulated with MADGRAPH5_aMC@NLO; PYTHIA 8 was used to simulate the parton shower, while the cross section was taken from Ref. [10]. In all signal and background samples, the mass of the H bosons was set to 125 GeV. The contributions from other SM Higgs boson processes are negligible. EVTGEN v1.2.0 [68] was used to model the properties of bottom and charm hadron decays for all processes except those simulated in SHERPA. The detector response to the generated events was simulated with GEANT4 [69,70]. Simulated events are reweighted to match the distribution of the number of inelastic collisions per event (pileup) in data.

Events are required to have at least one collision vertex reconstructed from at least two charged-particle tracks with transverse momentum [71] $p_T^{\rm track} > 0.4$ GeV. The primary vertex for each event is selected as the vertex with the highest $\sum (p_T^{\rm track})^2$. Jets are formed using the anti-k_t algorithm [72] with a radius parameter $R = 0.4$ and calorimeter energy clusters as inputs [73–75]. These jets are taken as seeds for the reconstruction of the visible products of hadronically decaying τ leptons ($\tau_{\rm had\text{-}vis}$) [76–78], which are subsequently required to have one or three associated tracks. In order to distinguish $\tau_{\rm had\text{-}vis}$ from quark- and gluon-initiated jets, a boosted decision tree (BDT) [79], trained separately for $\tau_{\rm had\text{-}vis}$ with one and three charged particles, is employed. Selected $\tau_{\rm had\text{-}vis}$ candidates must satisfy the "medium" BDT working point [77]. Electron candidates are identified using a likelihood technique in combination with additional track-hit requirements [80]; the transition region between the barrel and end cap calorimeters is excluded. Information from the tracking and muon systems is used to reconstruct muon candidates [81]. Only isolated electrons and muons are considered, where no nearby tracks or calorimeter energy deposits within a p_T-dependent variable-size ΔR cone around the lepton are allowed. Jets arising from pileup are suppressed using dedicated track and vertex requirements [82]. The missing transverse momentum, with magnitude $E_T^{\rm miss}$, is defined as the negative vectorial sum of all reconstructed and fully calibrated objects in the event, along with an additional track-based soft term [83]. Jets containing b hadrons are identified using the MV2c10 multivariate discriminant [84,85] trained against a light-quark-flavor sample also containing 10% of c hadrons. A working point with 70% efficiency on simulated $t\bar{t}$ events is used. An overlap-removal procedure is applied to the reconstructed electrons, muons, $\tau_{\rm had\text{-}vis}$, and jets to prevent double counting of energy deposits in the detector as described in Ref. [86].

The selected final state is characterized by one electron or muon and one $\tau_{\rm had\text{-}vis}$ of opposite charge, or two $\tau_{\rm had\text{-}vis}$ of opposite charge, plus two b-tagged jets and $E_T^{\rm miss}$. In all cases, events with additional electrons or muons above 7 GeV or $\tau_{\rm had\text{-}vis}$ above 20 GeV are rejected. The off-line selection criteria for the electron, muon, and $\tau_{\rm had\text{-}vis}$ depend on the triggers used. In the $\tau_{\rm lep}\tau_{\rm had}$ channel events are selected with a single-lepton trigger (SLT) and a lepton plus $\tau_{\rm had}$ trigger (LTT), which are analyzed separately and combined with the $\tau_{\rm had}\tau_{\rm had}$ channel in the final fit. Depending on the data period, the electron or muon that passes the SLT trigger is required to have $p_T >$ 25–27 GeV. Events which fail this requirement are considered for the LTT category if the electron (muon) has $p_T > 18$ GeV (15 GeV). In all cases, these p_T requirements are 1 GeV higher than the trigger thresholds to ensure a nearly constant trigger efficiency relative to the off-line selection. The $\tau_{\rm lep}\tau_{\rm had}$ events are required to have one $\tau_{\rm had\text{-}vis}$ candidate with $|\eta| < 2.3$ and $p_T > 20$ GeV for SLT events, raised to 30 GeV for LTT events due to $\tau_{\rm had\text{-}vis}$ p_T requirements applied in this category of triggers. In the $\tau_{\rm had}\tau_{\rm had}$ channel a logical OR of single $\tau_{\rm had}$ triggers (STT) and di-$\tau_{\rm had}$ triggers (DTT) is used. The leading $\tau_{\rm had\text{-}vis}$ candidate is required to have a minimum p_T of 40 GeV for DTT and between 100 and 180 GeV for STT events, depending on the data-taking period. The subleading $\tau_{\rm had\text{-}vis}$ is required to have a minimum p_T of 20 (30) GeV for STT (DTT) events. The leading jet is required to have

$p_T > 45$ GeV, except in the LTT and DTT channels where this is raised to 80 GeV due to a requirement on the presence of a jet at the Level 1 trigger to reduce the rate (during 2016 data taking only for the DTT). In all cases the subleading jet must have $p_T > 20$ GeV. The invariant mass of the di-τ system, $m_{\tau\tau}^{\mathrm{MMC}}$, is calculated using the Missing Mass Calculator [87] and is required to be greater than 60 GeV. Signal region (SR) events are defined as those meeting the criteria above, and in addition containing two b-tagged jets; they are further separated into $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ SLT, $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ LTT and $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ categories.

BDTs are used in the analysis to improve the separation of signal from background. Their distributions in the three signal regions, along with control region yields to constrain the normalization of the dominant backgrounds, form the inputs to the final fit. The BDTs for the $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel are trained against the main backgrounds, $t\bar{t}$, $Z \to \tau\tau$, and multijet events; in the $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel they are trained solely against the dominant $t\bar{t}$ background. For the BDT trainings, the $t\bar{t}$ and $Z \to \tau\tau$ backgrounds are taken purely from simulation, while the multi-jet events are estimated using the data-driven approach described below. Variables which provide good discrimination and are minimally correlated are used as inputs to the BDTs, as summarized in Table I. The variables selected in each channel differ, reflecting the different background compositions. In the resonant search, BDTs are trained separately for each signal mass considered, from 260 to 1000 GeV (800 GeV for LTT), where the signal model combines the target resonance mass and its two neighboring mass points, to be sensitive to masses between the simulated points. For NR HH production, the BDTs are trained on a signal sample with the SM admixture of the contributions from the box diagram and triangle diagram. The BDTs are more sensitive to the box diagram where the two Higgs bosons are produced at higher p_T and the selection efficiency is greater.

In both channels, simulated events are used to model background processes containing reconstructed $\tau_{\mathrm{had\text{-}vis}}$ that are matched to generated τ_{had} within $\Delta R = 0.2$ (subsequently referred to as true τ_{had}) and other minor background contributions. The rate of events with at least one true τ_{had} and a jet reconstructed as an electron or muon is found to be negligible. For $t\bar{t}$ background events containing one or more true τ_{had} the normalization is obtained in the final fit, constrained mainly by the low $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ BDT score regions, resulting in a normalization factor of 1.06 ± 0.13. The normalization of the $Z \to ee/\tau\tau +$ heavy-flavor background is determined using $Z \to \mu\mu +$ heavy-flavor events. Their selection closely follows the event selection used for signal events. Instead of two τ-lepton candidates, two muons with $p_T > 27$ GeV and dimuon invariant mass between 81 and 101 GeV are selected. To remove the contribution from SM $ZH(H \to bb)$ production, m_{bb} is required to be lower than 80 GeV or greater than 140 GeV. The normalization is determined by including the $Z \to \mu\mu +$ heavy-flavor control region yield in the final fit, resulting in a normalization factor of 1.34 ± 0.16. Normalization factors are not applied to the $Z +$ light-flavor contributions. The modeling of the BDT score

TABLE I. Variables used as inputs to the BDTs for the different channels and signal models. Here, m_{HH} is reconstructed from the $\tau\tau$ and bb systems using a 125 GeV Higgs mass constraint; $m_{\tau\tau}^{\mathrm{MMC}}$ is the invariant mass of the di-τ system, calculated using the Missing Mass Calculator [87]; m_{bb} is the invariant bb-mass; $\Delta R(\tau,\tau)$ is evaluated between the electron or muon and $\tau_{\mathrm{had\text{-}vis}}$ (two $\tau_{\mathrm{had\text{-}vis}}$) in the case of the $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ ($\tau_{\mathrm{had}}\tau_{\mathrm{had}}$) channel; E_T^{miss} ϕ centrality quantifies the relative angular position of the E_T^{miss} relative to the visible τ decay products in the transverse plane [88] and is defined as $(A+B)/(\sqrt{A^2+B^2})$, where $A = \sin(\phi_{E_T^{\mathrm{miss}}} - \phi_{\tau_2})/\sin(\phi_{\tau_1} - \phi_{\tau_2})$, $B = \sin(\phi_{\tau_1} - \phi_{E_T^{\mathrm{miss}}})/\sin(\phi_{\tau_1} - \phi_{\tau_2})$, and τ_1 and τ_2 stand for electron or muon and $\tau_{\mathrm{had\text{-}vis}}$ (two $\tau_{\mathrm{had\text{-}vis}}$) in the case of the $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ ($\tau_{\mathrm{had}}\tau_{\mathrm{had}}$) channel; m_T^W is the transverse mass of the lepton and the E_T^{miss}; $\Delta\phi(H,H)$ is the azimuthal angle between the two Higgs boson candidates; $\Delta p_T(\mathrm{lep}, \tau_{\mathrm{had\text{-}vis}})$ is the difference in p_T between the electron or muon and $\tau_{\mathrm{had\text{-}vis}}$.

Variable	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel (SLT resonant)	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel (SLT nonresonant & LTT)	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{\mathrm{MMC}}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	✓
E_T^{miss}	✓		
E_T^{miss} ϕ centrality	✓		✓
m_T^W	✓	✓	
$\Delta\phi(H,H)$	✓		
$\Delta p_T(\mathrm{lep}, \tau_{\mathrm{had\text{-}vis}})$	✓		
Subleading b-jet p_T	✓		

distributions is validated in the 0-b-tag and 1-b-tag regions as well as in dedicated $t\bar{t}$ and $Z+$ heavy-flavor validation regions.

Contributions from processes in which a quark- or gluon-initiated jet is misidentified as a $\tau_{\text{had-vis}}$ candidate (fake-τ_{had}) are estimated using data-driven methods for major backgrounds. A fake-τ_{had} enriched sample is defined by requiring that a $\tau_{\text{had-vis}}$ fails the "medium" BDT identification but satisfies a very loose requirement on the BDT score. This selection maintains a composition of quark- and gluon-initiated jets similar to those mimicking $\tau_{\text{had-vis}}$ in the SR. In the case where the event contains more than one such fake τ_{had}, one is chosen randomly. The SR selection, except for the $\tau_{\text{had-vis}}$ identification, is applied to the fake-τ_{had} enriched sample to extract template distributions for the fake-τ_{had} background after the true-τ_{had} contamination is subtracted using simulation. The templates are scaled with fake factors (FF) defined as the ratio of the number of fake τ_{had} that pass the $\tau_{\text{had-vis}}$ identification to the number that fail, calculated in dedicated control regions (CR) and parametrized in $p_T(\tau_{\text{had-vis}})$ and the number of associated tracks.

For the $\tau_{\text{lep}}\tau_{\text{had}}$ final state, fake-τ_{had} background contributions from $t\bar{t}$, $W+$jets and multijet processes are estimated using a combined fake-factor method similar to that described in Refs. [86,89]. In order to account for the different sources of fake τ_{had}, the FFs are derived separately for each background contribution. The CR for multijet events is defined by inverting the isolation requirement applied to the electron or muon for events with 0 or 1 b-tagged jets. The $t\bar{t}$ ($W+$jets) control region is defined by requiring two (zero) b-tagged jets and $m_T^W > 40$ GeV, where $m_T^W = \sqrt{2p_T^{\text{lep}}E_T^{\text{miss}}(1-\cos\Delta\phi_{\text{lep},E_T^{\text{miss}}})}$, and $\Delta\phi_{\text{lep},E_T^{\text{miss}}}$ is the azimuthal angle between the electron or muon and the E_T^{miss}. Fake factors for $t\bar{t}$ and $W+$jets are found to be consistent for both processes. The individual fake factors are then combined as $\text{FF(comb)} = \text{FF(QCD)} \times r_{\text{QCD}} + \text{FF}(t\bar{t}/W+\text{jets}) \times (1 - r_{\text{QCD}})$, where r_{QCD} is defined as the fraction of fake τ_{had} from (predominantly multijet) processes contributing to the data in the fake τ_{had} enriched template region that are not accounted for by simulated background processes, and is less than 5% in the 2-b-tag region. Because of the different origin of fake τ_{had}, the FFs for $t\bar{t}/W+$jets can be up to 30% larger than those for multijet processes. Events with two b-tagged jets but a same-sign charge (SS) electron or muon and $\tau_{\text{had-vis}}$ are used for validating the fake-τ_{had} background, showing all distributions are well modeled. Given this, and the small size of the contribution, no transfer factor is applied to correct the multijet estimation from the 1-b-tag region to the 2-b-tag region.

In the $\tau_{\text{had}}\tau_{\text{had}}$ final state, only the multijet background is estimated from data using the FF method. The differential FFs are derived in a 1-b-tag SS control region, while the overall normalization is taken from the 2-b-tag SS control region. The $t\bar{t}$ background is estimated from simulation, where the fake-τ_{had} $t\bar{t}$ contribution is corrected in bins of $\eta(\tau_{\text{had-vis}})$ using the probability for a jet from a hadronic W-boson decay to mimic a $\tau_{\text{had-vis}}$ candidate (fake rate), as measured with data in the $\tau_{\text{lep}}\tau_{\text{had}}$ $t\bar{t}$ control region [86]. Contributions from true τ_{had} are subtracted using simulation.

The uncertainty in the integrated luminosity of the combined $2015+2016$ data set is 2.1% [90] and is applied to the signal and background components whose normalizations are derived from simulation. An uncertainty related to the pileup reweighting procedure is also applied [91]. Experimental uncertainties in the identification and reconstruction of the electron [92], muon [93], $\tau_{\text{had-vis}}$ [76], and jets [74,94] are accounted for and propagated through the analysis to determine their effect on the final results. These affect the trigger requirements, the identification and reconstruction efficiencies, the isolation, and the reconstructed energies and their resolutions. The uncertainties are propagated to the calculation of the E_T^{miss} [83], which has an additional uncertainty from the soft term. The uncertainties with the largest impact on the result are those related to the $\tau_{\text{had-vis}}$ identification efficiency, which correspond to an uncertainty of 16% on the NR signal strength, i.e., the simulated NR HH yield assuming a cross-section times branching fraction equal to the expected limit and normalized to the SM expectation ($\sigma^{\text{exp}}/\sigma^{\text{SM}}$). Uncertainties in flavor tagging [95,96] also have a significant impact, inducing an uncertainty in the NR signal strength of 8.3%, dominated by those associated with the b-tagging efficiency.

Theory uncertainties in the modeling of the $t\bar{t}$ background containing one or more true τ_{had} are assessed by varying the matrix element generator (using aMC@NLO instead of POWHEG-BOX) and the parton shower model (using HERWIG++ instead of PYTHIA 6), and by adjusting the factorization and renormalization scales along with the amount of additional radiation. The resulting variations in the BDT distributions are included as shape uncertainties in the final fit. In order to account for potential acceptance differences between control and signal regions, the normalization of the $t\bar{t}$ background containing true τ_{had}, determined predominantly from the $\tau_{\text{lep}}\tau_{\text{had}}$ SR in the final fit, is allowed to vary within a range determined by the acceptance variations associated with the $t\bar{t}$ modeling uncertainties. This amounts to $+30\%/-32\%$ for the $\tau_{\text{had}}\tau_{\text{had}}$ SR and $+8.1\%/-9.3\%$ for the $Z\to\mu\mu+$heavy-flavor control region. This is the dominant uncertainty in the $t\bar{t}$ modeling.

For the $Z+$jets background, the theory uncertainties in the modeling of the BDT shapes are derived by comparing the nominal SHERPA sample with an alternative MADGRAPH5_aMC@NLO + PYTHIA 8 sample and by varying the choice of renormalization and factorization scales, along with the PDF prescription [97]. The normalization of the $Z\to\tau\tau+$heavy-flavor background in the

$\tau_{\rm lep}\tau_{\rm had}$ ($\tau_{\rm had}\tau_{\rm had}$) SR is allowed to vary by 29% (35%) relative to the normalization derived in the $Z \to \mu\mu +$ heavy-flavor control region in order to account for acceptance differences between the two. An additional 20% normalization uncertainty in the $Z \to ee +$ light-flavor background, related to the misidentification of electrons as taus, is derived by comparing data and simulation in a $Z \to ee$ control region with 0 or 1 b-tagged jets. The ZH (ttH) background normalization is varied by 28% (30%) based on ATLAS measurements [98,99]. The normalizations of the remaining minor backgrounds taken from simulation are allowed to vary within their respective cross-section uncertainties.

The uncertainty in the modeling of backgrounds due to jets being misidentified as $\tau_{\text{had-vis}}$ is estimated by varying the fake factors and fake rates within their statistical uncertainties and varying the amount of true-$\tau_{\rm had}$ background subtracted. Based on studies with simulated $t\bar{t}$ and $W +$ jets events, a systematic uncertainty is assigned to cover the difference in the gluon and quark flavor composition of jets misidentified as a $\tau_{\text{had-vis}}$ between the signal region and the fake-$\tau_{\rm had}$ enriched sample, parametrized as a function of the $\tau_{\text{had-vis}}$ identification BDT score. The uncertainty in the extrapolation of FF(QCD) to the signal region is estimated from the difference between the nominal FFs and alternative ones, calculated either in the SS region for the $\tau_{\rm lep}\tau_{\rm had}$ channel or a multijet enriched region, where $\Delta\phi(\tau_{\text{had-vis}}, \tau_{\text{had-vis}}) > 2.0$, in the $\tau_{\rm had}\tau_{\rm had}$ case. Similarly, changes in the fake-$\tau_{\rm had}$ determination when varying the $t\bar{t}$ control region m_T^W requirement in simulation and data are used to estimate a systematic uncertainty in both the fake factors and fake rates. The overall effect of these uncertainties on the fake-$\tau_{\rm had}$ background estimate leads to an 8.4% variation of the NR signal strength, predominantly due to the true-$\tau_{\rm had}$ subtraction in the $t\bar{t}$ control region and the composition of the fake $\tau_{\rm had}$.

Theory uncertainties in the signal acceptance are calculated by independently varying the renormalization and factorization scales, the choice of PDF and each PDF set by its uncertainties. The uncertainty in the parton shower is taken into account by comparing the default HERWIG++ with PYTHIA 8. Uncertainties in the underlying event, initial-state radiation and final-state radiation are accounted for by changing the PYTHIA tune, but are small. The effects of various categories of uncertainty on the measured nonresonant signal strength corresponding to the expected upper limit at 95% C.L. are summarized in Table II. The individual sources of uncertainty making up the categories listed in the table are grouped together in the final fit to determine their correlated combined effect on the signal strength. For all signal hypotheses, the statistical uncertainties dominate.

For each signal model considered, a profile-likelihood fit [100] is applied to the BDT score distributions simultaneously in the three SRs to extract the signal cross section, along with the $t\bar{t}$ and $Z +$ heavy-flavor normalizations. The lattermost is constrained by including the dedicated control region in the fit. All sources of systematic and statistical uncertainty in the signal and background models are implemented as deviations from the nominal model, scaled by nuisance parameters that are profiled in the fit. None of the dominant nuisance parameters are significantly constrained or pulled relative to their input value by the fit. The BDT score distributions for the nonresonant search and the $G_{\rm KK}$ signal are shown in Fig. 1 after performing the fit and assuming a background-only hypothesis. The acceptance times efficiency for the NR HH signal is 4.2% (2.9%) in the combined SLT and LTT $\tau_{\rm lep}\tau_{\rm had}$ ($\tau_{\rm had}\tau_{\rm had}$) channel over the full BDT distribution, decreasing to 3.3% (2.4%) for the two most sensitive BDT bins. As no significant excess over the expected background is observed, upper limits are set on nonresonant and resonant Higgs boson pair production at 95% C.L. using the CL_s method [101].

TABLE II. The percentage uncertainties on the simulated nonresonant signal strength, i.e., the simulated NR HH yield assuming a cross-section times branching fraction equal to the 95% C.L. expected limit of 14.8 times the SM expectation.

Source	Uncertainty (%)
Total	±54
Data statistics	±44
Simulation statistics	±16
Experimental uncertainties	
Luminosity	±2.4
Pileup reweighting	±1.7
$\tau_{\rm had}$	±16
Fake-τ estimation	±8.4
b tagging	±8.3
Jets and $E_T^{\rm miss}$	±3.3
Electron and muon	±0.5
Theoretical and modeling uncertainties	
Top	±17
Signal	±9.3
$Z \to \tau\tau$	±6.8
SM Higgs	±2.9
Other backgrounds	±0.3

Table III presents the upper limits on the cross section for nonresonant HH production times the $HH \to bb\tau\tau$ branching ratio, and comparisons with the SM prediction. The observed (expected) limit is 30.9 fb (36.0 fb), 12.7 (14.8) times the SM prediction. In order to compare with previous results, the BDTs are trained and applied to the signal sample without reweighting the m_{HH} spectrum to Refs. [9,31], giving an observed (expected) limit of 37.4 fb (33.5 fb), 15.4 (13.8) times the SM prediction.

The results of searches for resonant HH production are presented as exclusion limits on the cross-section times the $HH \to bb\tau\tau$ branching ratio as a function of the resonance mass. The expected and observed limits for narrow-width

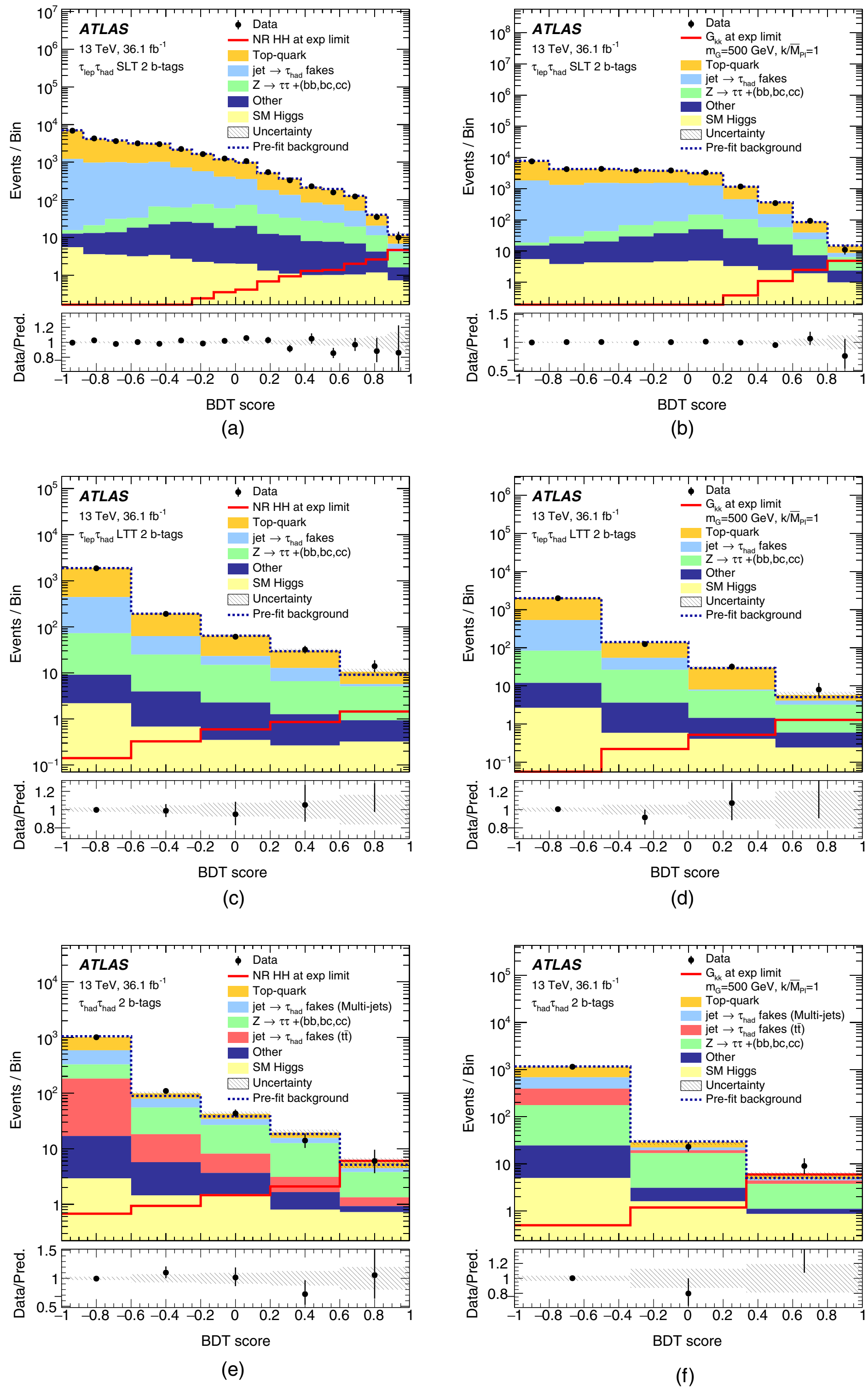

FIG. 1. Distributions of the BDT score for NR HH signal (left) and bulk RS signal with $m_{G_{KK}} = 500$ GeV and $k/\bar{M}_{Pl} = 1$ (right) in the (a),(b) $\tau_{lep}\tau_{had}$ single-lepton trigger (SLT), (c),(d) lepton + τ_{had} trigger (LTT) and (e),(f) $\tau_{had}\tau_{had}$ channels. Distributions are shown after the fit to the background-only hypothesis and the signal is scaled to approximately the expected limit. The hatched band indicates the combined statistical and systematic uncertainty in the background. The ratio of the data to the sum of the backgrounds is shown in the lower panel.

TABLE III. Observed and expected upper limits on the production cross-section times the $HH \to bb\tau\tau$ branching ratio for NR HH at 95% C.L., and their ratios to the SM prediction. The $\pm 1\sigma$ variations about the expected limit are also shown.

		Observed	-1σ	Expected	$+1\sigma$
$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\sigma(HH \to bb\tau\tau)$ [fb]	57	49.9	69	96
	$\sigma/\sigma_{\mathrm{SM}}$	23.5	20.5	28.4	39.5
$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\sigma(HH \to bb\tau\tau)$ [fb]	40.0	30.6	42.4	59
	$\sigma/\sigma_{\mathrm{SM}}$	16.4	12.5	17.4	24.2
Combination	$\sigma(HH \to bb\tau\tau)$ [fb]	30.9	26.0	36.1	50
	$\sigma/\sigma_{\mathrm{SM}}$	12.7	10.7	14.8	20.6

scalar resonances X and G_{KK} signal models are shown in Fig. 2. For scalar resonances, the results are interpreted in a simplified minimal supersymmetric model, the hMSSM [102,103], where the mass of the light CP-even Higgs boson is fixed to 125 GeV. The mass range 305 GeV $< m_X <$ 402 GeV is excluded at 95% C.L. for $\tan\beta = 2$, where $\tan\beta$ is the ratio of the vacuum expectation values of the scalar doublets. Gravitons are excluded at 95% C.L. in the mass range 325 GeV $< m_{G_{\mathrm{KK}}} <$ 85 GeV assuming $k/\bar{M}_{\mathrm{Pl}} = 1$. Above $\sim$600 GeV, the limits are largely insensitive to the value of $k/\bar{M}_{\mathrm{Pl}}$, while at low m_{HH} they improve significantly with increasing k due to the larger natural width. The limits on resonant HH production are significantly more stringent than previous results in the $bb\tau\tau$ channel and competitive with limits obtained in other channels.

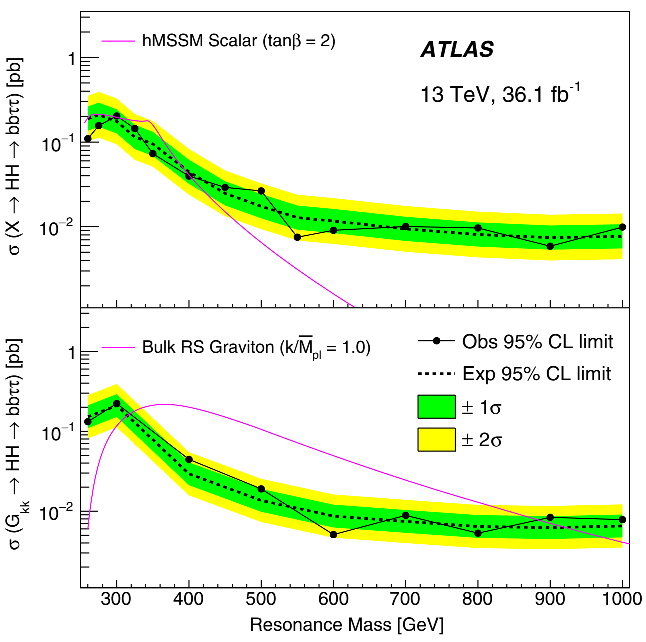

FIG. 2. Observed and expected limits at 95% C.L. on the cross sections of a generic narrow-width scalar X (top) and RS G_{KK} (bottom) times the branching fraction to two CP-even Higgs bosons H, when combining the $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ and $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channels. The expected cross section for the hMSSM scalar X production at $\tan\beta = 2$ and the bulk RS graviton production with $k/\bar{M}_{\mathrm{Pl}} = 1.0$ are also shown in the respective plots. In the hMSSM case, the bump in the theory prediction around 350 GeV corresponds to the threshold for X decaying into $t\bar{t}$ pairs.

In summary, a search for resonant and nonresonant Higgs boson pair production in the $bb\tau\tau$ final state is conducted with 36.1 fb^{-1} of pp collision data delivered by the LHC at $\sqrt{s} = 13$ TeV and recorded by the ATLAS detector. The analysis of nonresonant Higgs pair production excludes an enhancement of the SM expectation by more than a factor of 12.7 at 95% C.L. This is the most stringent limit on HH production to date. Upper limits are set on resonant Higgs boson pair production for a narrow-width scalar X and a spin-2 Kaluza-Klein graviton G_{KK} in the bulk RS model.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [104].

[1] ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B **716**, 1 (2012).

[2] CMS Collaboration, Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV, J. High Energy Phys. 06 (2013) 081.

[3] ATLAS and CMS Collaborations, Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments, Phys. Rev. Lett. **114**, 191803 (2015).

[4] F. Englert and R. Brout, Broken Symmetry and the Mass of Gauge Vector Mesons, Phys. Rev. Lett. **13**, 321 (1964).

[5] P. W. Higgs, Broken Symmetries and the Masses of Gauge Bosons, Phys. Rev. Lett. **13**, 508 (1964).

[6] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Global Conservation Laws and Massless Particles, Phys. Rev. Lett. **13**, 585 (1964).

[7] P. W. Higgs, Spontaneous symmetry breakdown without massless bosons, Phys. Rev. **145**, 1156 (1966).

[8] T. W. B. Kibble, Symmetry breaking in non-Abelian gauge theories, Phys. Rev. **155**, 1554 (1967).

[9] S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk, U. Schubert, and T. Zirke, Higgs Boson Pair Production in Gluon Fusion at Next-to-Leading Order with Full Top-Quark Mass Dependence, Phys. Rev. Lett. **117**, 012001 (2016); Erratum, Phys. Rev. Lett. **117**, 079901(E) (2016).

[10] D. de Florian *et al.*, Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector, CERN Report No. CERN-2017-002-M, 2016, https://cds.cern.ch/record/2227475/.

[11] G. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, Theory and phenomenology of two-Higgs-doublet models, Phys. Rep. **516**, 1 (2012).

[12] L. Randall and R. Sundrum, A Large Mass Hierarchy from a Small Extra Dimension, Phys. Rev. Lett. **83**, 3370 (1999).

[13] K. Agashe, H. Davoudiasl, G. Perez, and A. Soni, Warped gravitons at the CERN LHC and beyond, Phys. Rev. D **76**, 036006 (2007).

[14] A. L. Fitzpatrick, J. Kaplan, L. Randall, and L.-T. Wang, Searching for the Kaluza-Klein graviton in bulk RS Models, J. High Energy Phys. 09 (2007) 013.

[15] ATLAS Collaboration, The ATLAS experiment at the CERN Large Hadron Collider, J. Instrum. **3**, S08003 (2008).

[16] ATLAS Collaboration, ATLAS insertable B-layer technical design report, CERN Reports No. CERN-LHCC-2010-013 and No. ATLAS-TDR-19, 2010, https://cds.cern.ch/record/1291633.

[17] ATLAS Collaboration, Searches for Higgs boson pair production in the $hh \to bb\tau\tau$, $\gamma\gamma WW^*$, $\gamma\gamma bb$, $bbbb$ channels with the ATLAS detector, Phys. Rev. D **92**, 092004 (2015).

[18] ATLAS Collaboration, Search for Higgs Boson pair production in the $b\bar{b}b\bar{b}$ final state from pp collision at $\sqrt{s} = 8$ TeV with the ATLAS detector, Eur. Phys. J. C **75**, 412 (2015).

[19] ATLAS Collaboration, Search For Higgs Boson Pair Production in the $\gamma\gamma b\bar{b}$ Final State Using pp Collision Data at $\sqrt{s} = 8$ TeV from the ATLAS Detector, Phys. Rev. Lett. **114**, 081802 (2015).

[20] ATLAS Collaboration, Search for pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state using proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, arXiv:1804.06174.

[21] CMS Collaboration, Search for Higgs boson pair production in events with two bottom quarks and two tau leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B **778**, 101 (2018).

[22] CMS Collaboration, Search for a massive resonance decaying to a pair of Higgs bosons in the four b quark final state in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B **781**, 244 (2018).

[23] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079.

[24] R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, P. Torrielli, E. Vryonidou, and M. Zaro, Higgs pair production at the LHC with NLO and parton-shower effects, Phys. Lett. B **732**, 142 (2014).

[25] S. Dawson, S. Dittmaier, and M. Spira, Neutral Higgs-boson pair production at hadron colliders: QCD corrections, Phys. Rev. D **58**, 115012 (1998).

[26] T. Plehn, M. Spira, and P. M. Zerwas, Pair production of neutral Higgs particles in gluon-gluon collisions, Nucl. Phys. **B479**, 46 (1996); Erratum, Nucl. Phys. **B531**, 655(E) (1998).

[27] R. Grober, M. Muhlleitner, M. Spira, and J. Streicher, NLO QCD corrections to Higgs pair production including dimension-6 operators, J. High Energy Phys. 09 (2015) 092.

[28] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, J. Pumplin, and C. P. Yuan, New parton distributions for collider physics, Phys. Rev. D **82**, 074024 (2010).

[29] M. Bahr *et al.*, HERWIG++ physics and manual, Eur. Phys. J. C **58**, 639 (2008).

[30] S. Gieseke, C. Rohr, and A. Siodmok, Colour reconnections in HERWIG++, Eur. Phys. J. C **72**, 2225 (2012).

[31] S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk, and T. Zirke, Full top quark mass dependence in Higgs boson pair production at NLO, J. High Energy Phys. 10 (2016) 107.

[32] S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk, U. Schubert, and T. Zirke, Higgs Boson Pair Production in Gluon Fusion at Next-to-Leading Order with Full Top-Quark Mass Dependence, Phys. Rev. Lett. **117**, 012001 (2016); **117**, 079901(E) (2016).

[33] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. **178**, 852 (2008).

[34] ATLAS Collaboration, ATLAS PYTHIA 8 tunes to 7 TeV data, CERN Report No. ATL-PHYS-PUB-2014-021, 2014, https://cds.cern.ch/record/1966419.

[35] R. D. Ball *et al.*, Parton distributions with LHC data, Nucl. Phys. **B867**, 244 (2013).

[36] A. Oliveira, Gravity particles from Warped Extra Dimensions, predictions for LHC, arXiv:1404.0102.

[37] Equivalently, Z bosons produced in association with at least one light-flavor quark (u, d, or s) are referred to as $Z+$ light-flavor.

[38] The notations $\tau\tau$ and bb are used throughout this Letter, in place of $\tau^+\tau^-$ and $b\bar{b}$, as charge conjugation is implied.

[39] S. Alioli, P. Nason, C. Oleari, and E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, J. High Energy Phys. 06 (2010) 043.

[40] P. Artoisenet, R. Frederix, O. Mattelaer, and R. Rietkerk, Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations, J. High Energy Phys. 03 (2013) 015.

[41] T. Sjöstrand, S. Mrenna, and P. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026.

[42] P. Z. Skands, Tuning Monte Carlo generators: The Perugia tunes, Phys. Rev. D **82**, 074018 (2010).

[43] M. Czakon, M. L. Mangano, A. Mitov, and J. Rojo, Constraints on the gluon PDF from top quark pair production at hadron colliders, J. High Energy Phys. 07 (2013) 167.

[44] M. Aliev, H. Lacker, U. Langenfeld, S. Moch, P. Uwer, and M. Wiedermann, HATHOR: HAdronic Top and Heavy quarks crOss section calculatoR, Comput. Phys. Commun. **182**, 1034 (2011).

[45] P. Kant, O. M. Kind, T. Kintscher, T. Lohse, T. Martini, S. Mölbitz, P. Rieck, and P. Uwer, HatHor for single top-quark production: Updated predictions and uncertainty estimates for single top-quark production in hadronic collisions, Comput. Phys. Commun. **191**, 74 (2015).

[46] N. Kidonakis, Two-loop soft anomalous dimensions for single top quark associated production with a W^- or H^-, Phys. Rev. D **82**, 054018 (2010).

[47] T. Gleisberg, S. Höche, F. Krauss, M. Schönherr, S. Schumann, F. Siegert, and J. Winter, Event generation with SHERPA 1.1, J. High Energy Phys. 02 (2009) 007.

[48] T. Gleisberg and S. Höche, Comix, a new matrix element generator, J. High Energy Phys. 12 (2008) 039.

[49] F. Cascioli, P. Maierhofer, and S. Pozzorini, Scattering Amplitudes with Open Loops, Phys. Rev. Lett. **108**, 111601 (2012).

[50] S. Schumann and F. Krauss, A parton shower algorithm based on Catani-Seymour dipole factorisation, J. High Energy Phys. 03 (2008) 038.

[51] S. Höche, F. Krauss, M. Schönherr, and F. Siegert, QCD matrix elements + parton showers: The NLO case, J. High Energy Phys. 04 (2013) 027.

[52] R. D. Ball *et al.*, Parton distributions for the LHC Run II, J. High Energy Phys. 04 (2015) 040.

[53] C. Anastasiou, L. J. Dixon, K. Melnikov, and F. Petriello, High precision QCD at hadron colliders: Electroweak gauge boson rapidity distributions at NNLO, Phys. Rev. D **69**, 094008 (2004).

[54] M. L. Ciccolini, S. Dittmaier, and M. Krämer, Electroweak radiative corrections to associated WH and ZH production at hadron colliders, Phys. Rev. D **68**, 073003 (2003).

[55] O. Brein, A. Djouadi, and R. V. Harlander, NNLO QCD corrections to the Higgs-strahlung processes at hadron colliders, Phys. Lett. B **579**, 149 (2004).

[56] G. Ferrera, M. Grazzini, and F. Tramontano, Associated Higgs-W-Bosons Production at Hadron Colliders: A Fully Exclusive QCD Calculation at NNLO, Phys. Rev. Lett. **107**, 152003 (2011).

[57] O. Brein, R. V. Harlander, M. Wiesemann, and T. Zirke, Top-quark mediated effects in hadronic Higgs-Strahlung, Eur. Phys. J. C **72**, 1868 (2012).

[58] G. Ferrera, M. Grazzini, and F. Tramontano, Higher-order QCD effects for associated WH production and decay at the LHC, J. High Energy Phys. 04 (2014) 039.

[59] G. Ferrera, M. Grazzini, and F. Tramontano, Associated ZH production at hadron colliders: The fully differential NNLO QCD calculation, Phys. Lett. B **740**, 51 (2015).

[60] J. M. Campbell, R. K. Ellis, and C. Williams, Associated production of a Higgs boson at NNLO, J. High Energy Phys. 06 (2016) 179.

[61] S. Alioli, P. Nason, C. Oleari, and E. Re, NLO Higgs boson production via gluon fusion matched with shower in POWHEG, J. High Energy Phys. 04 (2009) 002.

[62] ATLAS Collaboration, Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, J. High Energy Phys. 09 (2014) 145.

[63] L. Altenkamp, S. Dittmaier, R. V. Harlander, H. Rzehak, and T. Zirke, Gluon-induced Higgs-strahlung at next-to-leading order QCD, J. High Energy Phys. 02 (2013) 078.

[64] B. Hespel, F. Maltoni, and E. Vryonidou, Higgs and Z boson associated production via gluon fusion in the SM and the 2HDM, J. High Energy Phys. 06 (2015) 065.

[65] R. V. Harlander, A. Kulesza, V. Theeuwes, and T. Zirke, Soft gluon resummation for gluon-induced Higgs Strahlung, J. High Energy Phys. 11 (2014) 082.

[66] R. V. Harlander, S. Liebler, and T. Zirke, Higgs Strahlung at the Large Hadron Collider in the 2-Higgs-doublet model, J. High Energy Phys. 02 (2014) 023.

[67] O. Brein, R. V. Harlander, and T. J. E. Zirke, vh@nnlo—Higgs Strahlung at hadron colliders, Comput. Phys. Commun. **184**, 998 (2013).

[68] D. J. Lange, The EvtGen particle decay simulation package, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).

[69] S. Agostinelli *et al.*, Geant4—a simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).

[70] ATLAS Collaboration, The ATLAS simulation infrastructure, Eur. Phys. J. C **70**, 823 (2010).

[71] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points to the center of the LHC ring and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ is the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. The distance between two objects in η-ϕ space is $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Transverse momentum is defined by $p_T = p\sin\theta$.

[72] M. Cacciari, G. P. Salam, and G. Soyez, The anti-k_t jet clustering algorithm, J. High Energy Phys. 04 (2008) 063.

[73] ATLAS Collaboration, Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1, Eur. Phys. J. C **77**, 490 (2017).

[74] ATLAS Collaboration, Jet energy scale measurements and their systematic uncertainties in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. D **96**, 072002 (2017).

[75] ATLAS Collaboration, Tagging and suppression of pileup jets with the ATLAS detector, CERN Report No. ATLAS-CONF-2014-018, 2014, https://cds.cern.ch/record/1700870.

[76] ATLAS Collaboration, Measurement of the tau lepton reconstruction and identification performance in the ATLAS experiment using pp collisions at $\sqrt{s} = 13$ TeV, CERN Report No. ATLAS-CONF-2017-029, 2017, https://cds.cern.ch/record/2261772.

[77] ATLAS Collaboration, Reconstruction, Energy Calibration, and Identification of Hadronically Decaying Tau Leptons in the ATLAS Experiment for Run-2 of the LHC, CERN Report No. ATL-PHYS-PUB-2015-045, 2015, https://cds.cern.ch/record/2064383.

[78] ATLAS Collaboration, Identification and energy calibration of hadronically decaying tau leptons with the ATLAS experiment in pp collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C **75**, 303 (2015).

[79] A. Hoecker *et al.*, TMVA: Toolkit for Multivariate Data Analysis, Proc. Sci., ACAT2007 (**2007**) 040, https://pos.sissa.it/050/040/pdf.

[80] ATLAS Collaboration, Electron efficiency measurements with the ATLAS detector using the 2015 LHC proton-proton collision data, CERN Report No. ATLAS-CONF-2016-024, 2016, https://cds.cern.ch/record/2157687.

[81] ATLAS Collaboration, Muon reconstruction performance of the ATLAS detector in proton-proton collision data at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C **76**, 292 (2016).

[82] ATLAS Collaboration, Performance of pile-up mitigation techniques for jets in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector, Eur. Phys. J. C **76**, 581 (2016).

[83] ATLAS Collaboration, Performance of missing transverse momentum reconstruction with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV, arXiv:1802.08168.

[84] ATLAS Collaboration, Performance of b-Jet Identification in the ATLAS Experiment, J. Instrum. **11**, P04008 (2016).

[85] ATLAS Collaboration, Optimisation of the ATLAS b-tagging performance for the 2016 LHC Run, CERN Report No. ATL-PHYS-PUB-2016-012, 2016, https://cds.cern.ch/record/2160731.

[86] ATLAS Collaboration, Search for additional heavy neutral Higgs and gauge bosons in the ditau final state produced in 36 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 01 (2018) 055.

[87] A. Elagin, P. Murat, A. Pranko, and A. Safonov, A new mass reconstruction technique for resonances decaying to $\tau\tau$, Nucl. Instrum. Methods Phys. Res., Sect. A **654**, 481 (2011).

[88] ATLAS Collaboration, Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector, J. High Energy Phys. 04 (2015) 117.

[89] The fake-τ_{had} contribution of the $t\bar{t}$ background is estimated using the fake-factor method in the analysis, however, for the training of the BDTs the $t\bar{t}$ background is taken from simulation.

[90] ATLAS Collaboration, Luminosity determination in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector at the LHC, Eur. Phys. J. C **76**, 653 (2016).

[91] ATLAS Collaboration, Measurement of the Inelastic Proton-Proton Cross Section at $\sqrt{s} = 13$ TeV with the ATLAS Detector at the LHC, Phys. Rev. Lett. **117**, 182002 (2016).

[92] ATLAS Collaboration, Electron identification measurements in ATLAS using $\sqrt{s} = 13$ TeV data with 50 ns bunch spacing, CERN Report No. ATLAS-PHYS-PUB-2015-041, 2015, https://cds.cern.ch/record/2048202.

[93] ATLAS Collaboration, Muon reconstruction performance in early 13 TeV data, CERN Report No. ATLAS-PHYS-PUB-2015-037, 2015, https://cds.cern.ch/record/2047831.

[94] ATLAS Collaboration, Jet calibration and systematic uncertainties for jets reconstructed in the ATLAS detector at $\sqrt{s} = 13$ TeV, CERN Report No. ATLAS-PHYS-PUB-2015-015, 2015, https://cds.cern.ch/record/2037613.

[95] ATLAS Collaboration, Expected performance of the ATLAS b-tagging algorithms in Run-2, CERN Report No. ATL-PHYS-PUB-2015-022, 2015, https://cds.cern.ch/record/2037697.

[96] ATLAS Collaboration, Commissioning of the ATLAS b-tagging algorithms using $t\bar{t}$ events in early Run-2 data, CERN Report No. ATL-PHYS-PUB-2015-039, 2015, https://cds.cern.ch/record/2047871.

[97] J. Butterworth *et al.*, PDF4LHC recommendations for LHC Run II, J. Phys. G **43**, 023001 (2016).

[98] ATLAS Collaboration, Evidence for the $H \to b\bar{b}$ decay with the ATLAS detector, J. High Energy Phys. 12 (2017) 024.

[99] ATLAS Collaboration, Evidence for the associated production of the Higgs boson and a top quark pair with the ATLAS detector, Phys. Rev. D **97**, 072003 (2018).

[100] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C **71**, 1554 (2011); Erratum, **73**, 2501(E) (2013).

[101] A. L. Read, Presentation of search results: The CLs technique, J. Phys. G **28**, 2693 (2002).

[102] A. Djouadi and J. Quevillon, The MSSM Higgs sector at a high M_{SUSY}: reopening the low $\tan\beta$ regime and heavy Higgs searches, J. High Energy Phys. 10 (2013) 028.

[103] A. Djouadi, L. Maiani, G. Moreau, A. Polosa, J. Quevillon, and V. Riquer, The post-Higgs MSSM scenario: habemus MSSM?, Eur. Phys. J. C **73**, 2650 (2013).

[104] ATLAS Collaboration, ATLAS computing acknowledgements, CERN Report No. ATL-GEN-PUB-2016-002, https://cds.cern.ch/record/2202407.

M. Aaboud,[34d] G. Aad,[99] B. Abbott,[124] O. Abdinov,[13,a] B. Abeloos,[128] D. K. Abhayasinghe,[91] S. H. Abidi,[164] O. S. AbouZeid,[39] N. L. Abraham,[153] H. Abramowicz,[158] H. Abreu,[157] Y. Abulaiti,[6] B. S. Acharya,[64a,64b,b] S. Adachi,[160] L. Adamczyk,[81a] J. Adelman,[119] M. Adersberger,[112] A. Adiguzel,[12c,c] T. Adye,[141] A. A. Affolder,[143] Y. Afik,[157] C. Agheorghiesei,[27c] J. A. Aguilar-Saavedra,[136f,136a] F. Ahmadov,[77,d] G. Aielli,[71a,71b] S. Akatsuka,[83] T. P. A. Åkesson,[94] E. Akilli,[52] A. V. Akimov,[108] G. L. Alberghi,[23b,23a] J. Albert,[173] P. Albicocco,[49] M. J. Alconada Verzini,[86] S. Alderweireldt,[117] M. Aleksa,[35] I. N. Aleksandrov,[77] C. Alexa,[27b] T. Alexopoulos,[10] M. Alhroob,[124] B. Ali,[138] G. Alimonti,[66a] J. Alison,[36] S. P. Alkire,[145] C. Allaire,[128] B. M. M. Allbrooke,[153] B. W. Allen,[127] P. P. Allport,[21] A. Aloisio,[67a,67b] A. Alonso,[39] F. Alonso,[86] C. Alpigiani,[145] A. A. Alshehri,[55] M. I. Alstaty,[99] B. Alvarez Gonzalez,[35] D. Álvarez Piqueras,[171] M. G. Alviggi,[67a,67b] B. T. Amadio,[18] Y. Amaral Coutinho,[78b] L. Ambroz,[131] C. Amelung,[26] D. Amidei,[103] S. P. Amor Dos Santos,[136a,136c] S. Amoroso,[44] C. S. Amrouche,[52] C. Anastopoulos,[146] L. S. Ancu,[52] N. Andari,[142] T. Andeen,[11] C. F. Anders,[59b] J. K. Anders,[20] K. J. Anderson,[36] A. Andreazza,[66a,66b] V. Andrei,[59a] C. R. Anelli,[173] S. Angelidakis,[37] I. Angelozzi,[118] A. Angerami,[38] A. V. Anisenkov,[120b,120a] A. Annovi,[69a] C. Antel,[59a] M. T. Anthony,[146] M. Antonelli,[49] D. J. A. Antrim,[168] F. Anulli,[70a] M. Aoki,[79] J. A. Aparisi Pozo,[171] L. Aperio Bella,[35] G. Arabidze,[104] J. P. Araque,[136a] V. Araujo Ferraz,[78b] R. Araujo Pereira,[78b] A. T. H. Arce,[47] R. E. Ardell,[91] F. A. Arduh,[86] J-F. Arguin,[107] S. Argyropoulos,[75] A. J. Armbruster,[35] L. J. Armitage,[90] A Armstrong,[168] O. Arnaez,[164] H. Arnold,[118] M. Arratia,[31] O. Arslan,[24] A. Artamonov,[109,a] G. Artoni,[131] S. Artz,[97] S. Asai,[160] N. Asbah,[57] A. Ashkenazi,[158] E. M. Asimakopoulou,[169] L. Asquith,[153] K. Assamagan,[29] R. Astalos,[28a] R. J. Atkin,[32a] M. Atkinson,[170] N. B. Atlay,[148] K. Augsten,[138] G. Avolio,[35] R. Avramidou,[58a] M. K. Ayoub,[15a] G. Azuelos,[107,e] A. E. Baas,[59a] M. J. Baca,[21] H. Bachacou,[142] K. Bachas,[65a,65b] M. Backes,[131] P. Bagnaia,[70a,70b] M. Bahmani,[82] H. Bahrasemani,[149] A. J. Bailey,[171] J. T. Baines,[141] M. Bajic,[39] C. Bakalis,[10] O. K. Baker,[180] P. J. Bakker,[118] D. Bakshi Gupta,[93] E. M. Baldin,[120b,120a] P. Balek,[177] F. Balli,[142] W. K. Balunas,[133] J. Balz,[97] E. Banas,[82] A. Bandyopadhyay,[24] S. Banerjee,[178,f] A. A. E. Bannoura,[179] L. Barak,[158] W. M. Barbe,[37] E. L. Barberio,[102] D. Barberis,[53b,53a] M. Barbero,[99] T. Barillari,[113] M-S. Barisits,[35] J. Barkeloo,[127] T. Barklow,[150] N. Barlow,[31] R. Barnea,[157] S. L. Barnes,[58c] B. M. Barnett,[141] R. M. Barnett,[18] Z. Barnovska-Blenessy,[58a] A. Baroncelli,[72a] G. Barone,[26] A. J. Barr,[131] L. Barranco Navarro,[171] F. Barreiro,[96] J. Barreiro Guimarães da Costa,[15a] R. Bartoldus,[150] A. E. Barton,[87] P. Bartos,[28a] A. Basalaev,[134] A. Bassalat,[128] R. L. Bates,[55] S. J. Batista,[164] S. Batlamous,[34e] J. R. Batley,[31] M. Battaglia,[143] M. Bauce,[70a,70b] F. Bauer,[142] K. T. Bauer,[168] H. S. Bawa,[150,g] J. B. Beacham,[122] T. Beau,[132] P. H. Beauchemin,[167] P. Bechtle,[24] H. C. Beck,[51] H. P. Beck,[20,h] K. Becker,[50] M. Becker,[97] C. Becot,[44] A. Beddall,[12d] A. J. Beddall,[12a] V. A. Bednyakov,[77] M. Bedognetti,[118] C. P. Bee,[152] T. A. Beermann,[35] M. Begalli,[78b] M. Begel,[29] A. Behera,[152] J. K. Behr,[44] A. S. Bell,[92] G. Bella,[158] L. Bellagamba,[23b] A. Bellerive,[33] M. Bellomo,[157] P. Bellos,[9] K. Belotskiy,[110] N. L. Belyaev,[110] O. Benary,[158,a] D. Benchekroun,[34a] M. Bender,[112] N. Benekos,[10] Y. Benhammou,[158] E. Benhar Noccioli,[180] J. Benitez,[75] D. P. Benjamin,[47] M. Benoit,[52] J. R. Bensinger,[26] S. Bentvelsen,[118] L. Beresford,[131] M. Beretta,[49] D. Berge,[44] E. Bergeaas Kuutmann,[169] N. Berger,[5] L. J. Bergsten,[26] J. Beringer,[18] S. Berlendis,[7] N. R. Bernard,[100] G. Bernardi,[132] C. Bernius,[150] F. U. Bernlochner,[24] T. Berry,[91] P. Berta,[97] C. Bertella,[15a] G. Bertoli,[43a,43b] I. A. Bertram,[87] G. J. Besjes,[39] O. Bessidskaia Bylund,[179] M. Bessner,[44] N. Besson,[142] A. Bethani,[98] S. Bethke,[113] A. Betti,[24] A. J. Bevan,[90] J. Beyer,[113] R. M. B. Bianchi,[135] O. Biebel,[112] D. Biedermann,[19] R. Bielski,[35] K. Bierwagen,[97] N. V. Biesuz,[69a,69b] M. Biglietti,[72a] T. R. V. Billoud,[107] M. Bindi,[51] A. Bingul,[12d] C. Bini,[70a,70b] S. Biondi,[23b,23a] M. Birman,[177] T. Bisanz,[51] J. P. Biswal,[158] C. Bittrich,[46] D. M. Bjergaard,[47] J. E. Black,[150] K. M. Black,[25] T. Blazek,[28a] I. Bloch,[44] C. Blocker,[26] A. Blue,[55] U. Blumenschein,[90] Dr. Blunier,[144a] G. J. Bobbink,[118] V. S. Bobrovnikov,[120b,120a] S. S. Bocchetta,[94]

A. Bocci,[47] D. Boerner,[179] D. Bogavac,[112] A. G. Bogdanchikov,[120b,120a] C. Bohm,[43a] V. Boisvert,[91] P. Bokan,[169,i] T. Bold,[81a] A. S. Boldyrev,[111] A. E. Bolz,[59b] M. Bomben,[132] M. Bona,[90] J. S. Bonilla,[127] M. Boonekamp,[142] A. Borisov,[140] G. Borissov,[87] J. Bortfeldt,[35] D. Bortoletto,[131] V. Bortolotto,[71a,71b] D. Boscherini,[23b] M. Bosman,[14] J. D. Bossio Sola,[30] K. Bouaouda,[34a] J. Boudreau,[135] E. V. Bouhova-Thacker,[87] D. Boumediene,[37] C. Bourdarios,[128] S. K. Boutle,[55] A. Boveia,[122] J. Boyd,[35] D. Boye,[32b] I. R. Boyko,[77] A. J. Bozson,[91] J. Bracinik,[21] N. Brahimi,[99] A. Brandt,[8] G. Brandt,[179] O. Brandt,[59a] F. Braren,[44] U. Bratzler,[161] B. Brau,[100] J. E. Brau,[127] W. D. Breaden Madden,[55] K. Brendlinger,[44] L. Brenner,[44] R. Brenner,[169] S. Bressler,[177] B. Brickwedde,[97] D. L. Briglin,[21] D. Britton,[55] D. Britzger,[59b] I. Brock,[24] R. Brock,[104] G. Brooijmans,[38] T. Brooks,[91] W. K. Brooks,[144b] E. Brost,[119] J. H Broughton,[21] P. A. Bruckman de Renstrom,[82] D. Bruncko,[28b] A. Bruni,[23b] G. Bruni,[23b] L. S. Bruni,[118] S. Bruno,[71a,71b] B. H. Brunt,[31] M. Bruschi,[23b] N. Bruscino,[135] P. Bryant,[36] L. Bryngemark,[44] T. Buanes,[17] Q. Buat,[35] P. Buchholz,[148] A. G. Buckley,[55] I. A. Budagov,[77] F. Buehrer,[50] M. K. Bugge,[130] O. Bulekov,[110] D. Bullock,[8] T. J. Burch,[119] S. Burdin,[88] C. D. Burgard,[118] A. M. Burger,[5] B. Burghgrave,[119] K. Burka,[82] S. Burke,[141] I. Burmeister,[45] J. T. P. Burr,[131] D. Büscher,[50] V. Büscher,[97] E. Buschmann,[51] P. Bussey,[55] J. M. Butler,[25] C. M. Buttar,[55] J. M. Butterworth,[92] P. Butti,[35] W. Buttinger,[35] A. Buzatu,[155] A. R. Buzykaev,[120b,120a] G. Cabras,[23b,23a] S. Cabrera Urbán,[171] D. Caforio,[138] H. Cai,[170] V. M. M. Cairo,[2] O. Cakir,[4a] N. Calace,[52] P. Calafiura,[18] A. Calandri,[99] G. Calderini,[132] P. Calfayan,[63] G. Callea,[40b,40a] L. P. Caloba,[78b] S. Calvente Lopez,[96] D. Calvet,[37] S. Calvet,[37] T. P. Calvet,[152] M. Calvetti,[69a,69b] R. Camacho Toro,[132] S. Camarda,[35] P. Camarri,[71a,71b] D. Cameron,[130] R. Caminal Armadans,[100] C. Camincher,[35] S. Campana,[35] M. Campanelli,[92] A. Camplani,[39] A. Campoverde,[148] V. Canale,[67a,67b] M. Cano Bret,[58c] J. Cantero,[125] T. Cao,[158] Y. Cao,[170] M. D. M. Capeans Garrido,[35] I. Caprini,[27b] M. Caprini,[27b] M. Capua,[40b,40a] R. M. Carbone,[38] R. Cardarelli,[71a] F. C. Cardillo,[146] I. Carli,[139] T. Carli,[35] G. Carlino,[67a] B. T. Carlson,[135] L. Carminati,[66a,66b] R. M. D. Carney,[43a,43b] S. Caron,[117] E. Carquin,[144b] S. Carrá,[66a,66b] G. D. Carrillo-Montoya,[35] D. Casadei,[32b] M. P. Casado,[14,j] A. F. Casha,[164] D. W. Casper,[168] R. Castelijn,[118] F. L. Castillo,[171] V. Castillo Gimenez,[171] N. F. Castro,[136a,136e] A. Catinaccio,[35] J. R. Catmore,[130] A. Cattai,[35] J. Caudron,[24] V. Cavaliere,[29] E. Cavallaro,[14] D. Cavalli,[66a] M. Cavalli-Sforza,[14] V. Cavasinni,[69a,69b] E. Celebi,[12b] F. Ceradini,[72a,72b] L. Cerda Alberich,[171] A. S. Cerqueira,[78a] A. Cerri,[153] L. Cerrito,[71a,71b] F. Cerutti,[18] A. Cervelli,[23b,23a] S. A. Cetin,[12b] A. Chafaq,[34a] D Chakraborty,[119] S. K. Chan,[57] W. S. Chan,[118] Y. L. Chan,[61a] J. D. Chapman,[31] B. Chargeishvili,[156b] D. G. Charlton,[21] C. C. Chau,[33] C. A. Chavez Barajas,[153] S. Che,[122] A. Chegwidden,[104] S. Chekanov,[6] S. V. Chekulaev,[165a] G. A. Chelkov,[77,k] M. A. Chelstowska,[35] C. Chen,[58a] C. H. Chen,[76] H. Chen,[29] J. Chen,[58a] J. Chen,[38] S. Chen,[133] S. J. Chen,[15c] X. Chen,[15b,l] Y. Chen,[80] Y-H. Chen,[44] H. C. Cheng,[103] H. J. Cheng,[15d] A. Cheplakov,[77] E. Cheremushkina,[140] R. Cherkaoui El Moursli,[34e] E. Cheu,[7] K. Cheung,[62] L. Chevalier,[142] V. Chiarella,[49] G. Chiarelli,[69a] G. Chiodini,[65a] A. S. Chisholm,[35] A. Chitan,[27b] I. Chiu,[160] Y. H. Chiu,[173] M. V. Chizhov,[77] K. Choi,[63] A. R. Chomont,[128] S. Chouridou,[159] Y. S. Chow,[118] V. Christodoulou,[92] M. C. Chu,[61a] J. Chudoba,[137] A. J. Chuinard,[101] J. J. Chwastowski,[82] L. Chytka,[126] D. Cinca,[45] V. Cindro,[89] I. A. Cioară,[24] A. Ciocio,[18] F. Cirotto,[67a,67b] Z. H. Citron,[177] M. Citterio,[66a] A. Clark,[52] M. R. Clark,[38] P. J. Clark,[48] C. Clement,[43a,43b] Y. Coadou,[99] M. Cobal,[64a,64c] A. Coccaro,[53b,53a] J. Cochran,[76] H. Cohen,[158] A. E. C. Coimbra,[177] L. Colasurdo,[117] B. Cole,[38] A. P. Colijn,[118] J. Collot,[56] P. Conde Muiño,[136a,136b] E. Coniavitis,[50] S. H. Connell,[32b] I. A. Connelly,[98] S. Constantinescu,[27b] F. Conventi,[67a,m] A. M. Cooper-Sarkar,[131] F. Cormier,[172] K. J. R. Cormier,[164] M. Corradi,[70a,70b] E. E. Corrigan,[94] F. Corriveau,[101,n] A. Cortes-Gonzalez,[35] M. J. Costa,[171] D. Costanzo,[146] G. Cottin,[31] G. Cowan,[91] B. E. Cox,[98] J. Crane,[98] K. Cranmer,[121] S. J. Crawley,[55] R. A. Creager,[133] G. Cree,[33] S. Crépé-Renaudin,[56] F. Crescioli,[132] M. Cristinziani,[24] V. Croft,[121] G. Crosetti,[40b,40a] A. Cueto,[96] T. Cuhadar Donszelmann,[146] A. R. Cukierman,[150] J. Cúth,[97] S. Czekierda,[82] P. Czodrowski,[35] M. J. Da Cunha Sargedas De Sousa,[58b,136b] C. Da Via,[98] W. Dabrowski,[81a] T. Dado,[28a,i] S. Dahbi,[34e] T. Dai,[103] F. Dallaire,[107] C. Dallapiccola,[100] M. Dam,[39] G. D'amen,[23b,23a] J. Damp,[97] J. R. Dandoy,[133] M. F. Daneri,[30] N. P. Dang,[178,f] N. D Dann,[98] M. Danninger,[172] V. Dao,[35] G. Darbo,[53b] S. Darmora,[8] O. Dartsi,[5] A. Dattagupta,[127] T. Daubney,[44] S. D'Auria,[55] W. Davey,[24] C. David,[44] T. Davidek,[139] D. R. Davis,[47] E. Dawe,[102] I. Dawson,[146] K. De,[8] R. De Asmundis,[67a] A. De Benedetti,[124] M. De Beurs,[118] S. De Castro,[23b,23a] S. De Cecco,[70a,70b] N. De Groot,[117] P. de Jong,[118] H. De la Torre,[104] F. De Lorenzi,[76] A. De Maria,[51,o] D. De Pedis,[70a] A. De Salvo,[70a] U. De Sanctis,[71a,71b] M. De Santis,[71a,71b] A. De Santo,[153] K. De Vasconcelos Corga,[99] J. B. De Vivie De Regie,[128] C. Debenedetti,[143] D. V. Dedovich,[77] N. Dehghanian,[3] M. Del Gaudio,[40b,40a] J. Del Peso,[96] Y. Delabat Diaz,[44] D. Delgove,[128] F. Deliot,[142] C. M. Delitzsch,[7] M. Della Pietra,[67a,67b] D. Della Volpe,[52] A. Dell'Acqua,[35] L. Dell'Asta,[25] M. Delmastro,[5] C. Delporte,[128] P. A. Delsart,[56] D. A. DeMarco,[164] S. Demers,[180] M. Demichev,[77] S. P. Denisov,[140] D. Denysiuk,[118] L. D'Eramo,[132] D. Derendarz,[82] J. E. Derkaoui,[34d]

F. Derue,[132] P. Dervan,[88] K. Desch,[24] C. Deterre,[44] K. Dette,[164] M. R. Devesa,[30] P. O. Deviveiros,[35] A. Dewhurst,[141] S. Dhaliwal,[26] F. A. Di Bello,[52] A. Di Ciaccio,[71a,71b] L. Di Ciaccio,[5] W. K. Di Clemente,[133] C. Di Donato,[67a,67b] A. Di Girolamo,[35] B. Di Micco,[72a,72b] R. Di Nardo,[100] K. F. Di Petrillo,[57] R. Di Sipio,[164] D. Di Valentino,[33] C. Diaconu,[99] M. Diamond,[164] F. A. Dias,[39] T. Dias Do Vale,[136a] M. A. Diaz,[144a] J. Dickinson,[18] E. B. Diehl,[103] J. Dietrich,[19] S. Díez Cornell,[44] A. Dimitrievska,[18] J. Dingfelder,[24] F. Dittus,[35] F. Djama,[99] T. Djobava,[156b] J. I. Djuvsland,[59a] M. A. B. Do Vale,[78c] M. Dobre,[27b] D. Dodsworth,[26] C. Doglioni,[94] J. Dolejsi,[139] Z. Dolezal,[139] M. Donadelli,[78d] J. Donini,[37] A. D'onofrio,[90] M. D'Onofrio,[88] J. Dopke,[141] A. Doria,[67a] M. T. Dova,[86] A. T. Doyle,[55] E. Drechsler,[51] E. Dreyer,[149] T. Dreyer,[51] Y. Du,[58b] J. Duarte-Campderros,[158] F. Dubinin,[108] M. Dubovsky,[28a] A. Dubreuil,[52] E. Duchovni,[177] G. Duckeck,[112] A. Ducourthial,[132] O. A. Ducu,[107,p] D. Duda,[113] A. Dudarev,[35] A. C. Dudder,[97] E. M. Duffield,[18] L. Duflot,[128] M. Dührssen,[35] C. Dülsen,[179] M. Dumancic,[177] A. E. Dumitriu,[27b,q] A. K. Duncan,[55] M. Dunford,[59a] A. Duperrin,[99] H. Duran Yildiz,[4a] M. Düren,[54] A. Durglishvili,[156b] D. Duschinger,[46] B. Dutta,[44] D. Duvnjak,[1] M. Dyndal,[44] S. Dysch,[98] B. S. Dziedzic,[82] C. Eckardt,[44] K. M. Ecker,[113] R. C. Edgar,[103] T. Eifert,[35] G. Eigen,[17] K. Einsweiler,[18] T. Ekelof,[169] M. El Kacimi,[34c] R. El Kosseifi,[99] V. Ellajosyula,[99] M. Ellert,[169] F. Ellinghaus,[179] A. A. Elliot,[90] N. Ellis,[35] J. Elmsheuser,[29] M. Elsing,[35] D. Emeliyanov,[141] Y. Enari,[160] J. S. Ennis,[175] M. B. Epland,[47] J. Erdmann,[45] A. Ereditato,[20] S. Errede,[170] M. Escalier,[128] C. Escobar,[171] O. Estrada Pastor,[171] A. I. Etienvre,[142] E. Etzion,[158] H. Evans,[63] A. Ezhilov,[134] M. Ezzi,[34e] F. Fabbri,[55] L. Fabbri,[23b,23a] V. Fabiani,[117] G. Facini,[92] R. M. Faisca Rodrigues Pereira,[136a] R. M. Fakhrutdinov,[140] S. Falciano,[70a] P. J. Falke,[5] S. Falke,[5] J. Faltova,[139] Y. Fang,[15a] M. Fanti,[66a,66b] A. Farbin,[8] A. Farilla,[72a] E. M. Farina,[68a,68b] T. Farooque,[104] S. Farrell,[18] S. M. Farrington,[175] P. Farthouat,[35] F. Fassi,[34e] P. Fassnacht,[35] D. Fassouliotis,[9] M. Faucci Giannelli,[48] A. Favareto,[53b,53a] W. J. Fawcett,[31] L. Fayard,[128] O. L. Fedin,[134,r] W. Fedorko,[172] M. Feickert,[41] S. Feigl,[130] L. Feligioni,[99] C. Feng,[58b] E. J. Feng,[35] M. Feng,[47] M. J. Fenton,[55] A. B. Fenyuk,[140] L. Feremenga,[8] J. Ferrando,[44] A. Ferrari,[169] P. Ferrari,[118] R. Ferrari,[68a] D. E. Ferreira de Lima,[59b] A. Ferrer,[171] D. Ferrere,[52] C. Ferretti,[103] F. Fiedler,[97] A. Filipčič,[89] F. Filthaut,[117] K. D. Finelli,[25] M. C. N. Fiolhais,[136a,136c,s] L. Fiorini,[171] C. Fischer,[14] W. C. Fisher,[104] N. Flaschel,[44] I. Fleck,[148] P. Fleischmann,[103] R. R. M. Fletcher,[133] T. Flick,[179] B. M. Flierl,[112] L. M. Flores,[133] L. R. Flores Castillo,[61a] F. M. Follega,[73a,73b] N. Fomin,[17] G. T. Forcolin,[98] A. Formica,[142] F. A. Förster,[14] A. C. Forti,[98] A. G. Foster,[21] D. Fournier,[128] H. Fox,[87] S. Fracchia,[146] P. Francavilla,[69a,69b] M. Franchini,[23b,23a] S. Franchino,[59a] D. Francis,[35] L. Franconi,[130] M. Franklin,[57] M. Frate,[168] M. Fraternali,[68a,68b] A. N. Fray,[90] D. Freeborn,[92] S. M. Fressard-Batraneanu,[35] B. Freund,[107] W. S. Freund,[78b] D. C. Frizzell,[124] D. Froidevaux,[35] J. A. Frost,[131] C. Fukunaga,[161] E. Fullana Torregrosa,[171] T. Fusayasu,[114] J. Fuster,[171] O. Gabizon,[157] A. Gabrielli,[23b,23a] A. Gabrielli,[18] G. P. Gach,[81a] S. Gadatsch,[52] P. Gadow,[113] G. Gagliardi,[53b,53a] L. G. Gagnon,[107] C. Galea,[27b] B. Galhardo,[136a,136c] E. J. Gallas,[131] B. J. Gallop,[141] P. Gallus,[138] G. Galster,[39] R. Gamboa Goni,[90] K. K. Gan,[122] S. Ganguly,[177] J. Gao,[58a] Y. Gao,[88] Y. S. Gao,[150,g] C. García,[171] J. E. García Navarro,[171] J. A. García Pascual,[15a] M. Garcia-Sciveres,[18] R. W. Gardner,[36] N. Garelli,[150] V. Garonne,[130] K. Gasnikova,[44] A. Gaudiello,[53b,53a] G. Gaudio,[68a] I. L. Gavrilenko,[108] A. Gavrilyuk,[109] C. Gay,[172] G. Gaycken,[24] E. N. Gazis,[10] C. N. P. Gee,[141] J. Geisen,[51] M. Geisen,[97] M. P. Geisler,[59a] K. Gellerstedt,[43a,43b] C. Gemme,[53b] M. H. Genest,[56] C. Geng,[103] S. Gentile,[70a,70b] S. George,[91] D. Gerbaudo,[14] G. Gessner,[45] S. Ghasemi,[148] M. Ghasemi Bostanabad,[173] M. Ghneimat,[24] B. Giacobbe,[23b] S. Giagu,[70a,70b] N. Giangiacomi,[23b,23a] P. Giannetti,[69a] A. Giannini,[67a,67b] S. M. Gibson,[91] M. Gignac,[143] D. Gillberg,[33] G. Gilles,[179] D. M. Gingrich,[3,e] M. P. Giordani,[64a,64c] F. M. Giorgi,[23b] P. F. Giraud,[142] P. Giromini,[57] G. Giugliarelli,[64a,64c] D. Giugni,[66a] F. Giuli,[131] M. Giulini,[59b] S. Gkaitatzis,[159] I. Gkialas,[9,t] E. L. Gkougkousis,[14] P. Gkountoumis,[10] L. K. Gladilin,[111] C. Glasman,[96] J. Glatzer,[14] P. C. F. Glaysher,[44] A. Glazov,[44] M. Goblirsch-Kolb,[26] J. Godlewski,[82] S. Goldfarb,[102] T. Golling,[52] D. Golubkov,[140] A. Gomes,[136a,136b,136d] R. Goncalves Gama,[78a] R. Gonçalo,[136a] G. Gonella,[50] L. Gonella,[21] A. Gongadze,[77] F. Gonnella,[21] J. L. Gonski,[57] S. González de la Hoz,[171] S. Gonzalez-Sevilla,[52] L. Goossens,[35] P. A. Gorbounov,[109] H. A. Gordon,[29] B. Gorini,[35] E. Gorini,[65a,65b] A. Gorišek,[89] A. T. Goshaw,[47] C. Gössling,[45] M. I. Gostkin,[77] C. A. Gottardo,[24] C. R. Goudet,[128] D. Goujdami,[34c] A. G. Goussiou,[145] N. Govender,[32b,u] C. Goy,[5] E. Gozani,[157] I. Grabowska-Bold,[81a] P. O. J. Gradin,[169] E. C. Graham,[88] J. Gramling,[168] E. Gramstad,[130] S. Grancagnolo,[19] V. Gratchev,[134] P. M. Gravila,[27f] F. G. Gravili,[65a,65b] C. Gray,[55] H. M. Gray,[18] Z. D. Greenwood,[93,v] C. Grefe,[24] K. Gregersen,[94] I. M. Gregor,[44] P. Grenier,[150] K. Grevtsov,[44] N. A. Grieser,[124] J. Griffiths,[8] A. A. Grillo,[143] K. Grimm,[150] S. Grinstein,[14,w] Ph. Gris,[37] J.-F. Grivaz,[128] S. Groh,[97] E. Gross,[177] J. Grosse-Knetter,[51] G. C. Grossi,[93] Z. J. Grout,[92] C. Grud,[103] A. Grummer,[116] L. Guan,[103] W. Guan,[178] J. Guenther,[35] A. Guerguichon,[128] F. Guescini,[165a] D. Guest,[168] R. Gugel,[50] B. Gui,[122] T. Guillemin,[5] S. Guindon,[35] U. Gul,[55] C. Gumpert,[35] J. Guo,[58c] W. Guo,[103] Y. Guo,[58a,x] Z. Guo,[99] R. Gupta,[41] S. Gurbuz,[12c]

G. Gustavino,[124] B. J. Gutelman,[157] P. Gutierrez,[124] C. Gutschow,[92] C. Guyot,[142] M. P. Guzik,[81a] C. Gwenlan,[131] C. B. Gwilliam,[88] A. Haas,[121] C. Haber,[18] H. K. Hadavand,[8] N. Haddad,[34e] A. Hadef,[58a] S. Hageböck,[24] M. Hagihara,[166] H. Hakobyan,[181,a] M. Haleem,[174] J. Haley,[125] G. Halladjian,[104] G. D. Hallewell,[99] K. Hamacher,[179] P. Hamal,[126] K. Hamano,[173] A. Hamilton,[32a] G. N. Hamity,[146] K. Han,[58a,y] L. Han,[58a] S. Han,[15d] K. Hanagaki,[79,z] M. Hance,[143] D. M. Handl,[112] B. Haney,[133] R. Hankache,[132] P. Hanke,[59a] E. Hansen,[94] J. B. Hansen,[39] J. D. Hansen,[39] M. C. Hansen,[24] P. H. Hansen,[39] K. Hara,[166] A. S. Hard,[178] T. Harenberg,[179] S. Harkusha,[105] P. F. Harrison,[175] N. M. Hartmann,[112] Y. Hasegawa,[147] A. Hasib,[48] S. Hassani,[142] S. Haug,[20] R. Hauser,[104] L. Hauswald,[46] L. B. Havener,[38] M. Havranek,[138] C. M. Hawkes,[21] R. J. Hawkings,[35] D. Hayden,[104] C. Hayes,[152] C. P. Hays,[131] J. M. Hays,[90] H. S. Hayward,[88] S. J. Haywood,[141] M. P. Heath,[48] V. Hedberg,[94] L. Heelan,[8] S. Heer,[24] K. K. Heidegger,[50] J. Heilman,[33] S. Heim,[44] T. Heim,[18] B. Heinemann,[44,aa] J. J. Heinrich,[112] L. Heinrich,[121] C. Heinz,[54] J. Hejbal,[137] L. Helary,[35] A. Held,[172] S. Hellesund,[130] S. Hellman,[43a,43b] C. Helsens,[35] R. C. W. Henderson,[87] Y. Heng,[178] S. Henkelmann,[172] A. M. Henriques Correia,[35] G. H. Herbert,[19] H. Herde,[26] V. Herget,[174] Y. Hernández Jiménez,[32c] H. Herr,[97] M. G. Herrmann,[112] G. Herten,[50] R. Hertenberger,[112] L. Hervas,[35] T. C. Herwig,[133] G. G. Hesketh,[92] N. P. Hessey,[165a] J. W. Hetherly,[41] S. Higashino,[79] E. Higón-Rodriguez,[171] K. Hildebrand,[36] E. Hill,[173] J. C. Hill,[31] K. K. Hill,[29] K. H. Hiller,[44] S. J. Hillier,[21] M. Hils,[46] I. Hinchliffe,[18] M. Hirose,[129] D. Hirschbuehl,[179] B. Hiti,[89] O. Hladik,[137] D. R. Hlaluku,[32c] X. Hoad,[48] J. Hobbs,[152] N. Hod,[165a] M. C. Hodgkinson,[146] A. Hoecker,[35] M. R. Hoeferkamp,[116] F. Hoenig,[112] D. Hohn,[24] D. Hohov,[128] T. R. Holmes,[36] M. Holzbock,[112] M. Homann,[45] S. Honda,[166] T. Honda,[79] T. M. Hong,[135] A. Hönle,[113] B. H. Hooberman,[170] W. H. Hopkins,[127] Y. Horii,[115] P. Horn,[46] A. J. Horton,[149] L. A. Horyn,[36] J-Y. Hostachy,[56] A. Hostiuc,[145] S. Hou,[155] A. Hoummada,[34a] J. Howarth,[98] J. Hoya,[86] M. Hrabovsky,[126] J. Hrdinka,[35] I. Hristova,[19] J. Hrivnac,[128] A. Hrynevich,[106] T. Hryn'ova,[5] P. J. Hsu,[62] S.-C. Hsu,[145] Q. Hu,[29] S. Hu,[58c] Y. Huang,[15a] Z. Hubacek,[138] F. Hubaut,[99] M. Huebner,[24] F. Huegging,[24] T. B. Huffman,[131] E. W. Hughes,[38] M. Huhtinen,[35] R. F. H. Hunter,[33] P. Huo,[152] A. M. Hupe,[33] N. Huseynov,[77,d] J. Huston,[104] J. Huth,[57] R. Hyneman,[103] G. Iacobucci,[52] G. Iakovidis,[29] I. Ibragimov,[148] L. Iconomidou-Fayard,[128] Z. Idrissi,[34e] P. Iengo,[35] R. Ignazzi,[39] O. Igonkina,[118,bb] R. Iguchi,[160] T. Iizawa,[52] Y. Ikegami,[79] M. Ikeno,[79] D. Iliadis,[159] N. Ilic,[150] F. Iltzsche,[46] G. Introzzi,[68a,68b] M. Iodice,[72a] K. Iordanidou,[38] V. Ippolito,[70a,70b] M. F. Isacson,[169] N. Ishijima,[129] M. Ishino,[160] M. Ishitsuka,[162] W. Islam,[125] C. Issever,[131] S. Istin,[157] F. Ito,[166] J. M. Iturbe Ponce,[61a] R. Iuppa,[73a,73b] A. Ivina,[177] H. Iwasaki,[79] J. M. Izen,[42] V. Izzo,[67a] P. Jacka,[137] P. Jackson,[1] R. M. Jacobs,[24] V. Jain,[2] G. Jäkel,[179] K. B. Jakobi,[97] K. Jakobs,[50] S. Jakobsen,[74] T. Jakoubek,[137] D. O. Jamin,[125] D. K. Jana,[93] R. Jansky,[52] J. Janssen,[24] M. Janus,[51] P. A. Janus,[81a] G. Jarlskog,[94] N. Javadov,[77,d] T. Javůrek,[35] M. Javurkova,[50] F. Jeanneau,[142] L. Jeanty,[18] J. Jejelava,[156a,cc] A. Jelinskas,[175] P. Jenni,[50,dd] J. Jeong,[44] S. Jézéquel,[5] H. Ji,[178] J. Jia,[152] H. Jiang,[76] Y. Jiang,[58a] Z. Jiang,[150,ee] S. Jiggins,[50] F. A. Jimenez Morales,[37] J. Jimenez Pena,[171] S. Jin,[15c] A. Jinaru,[27b] O. Jinnouchi,[162] H. Jivan,[32c] P. Johansson,[146] K. A. Johns,[7] C. A. Johnson,[63] W. J. Johnson,[145] K. Jon-And,[43a,43b] R. W. L. Jones,[87] S. D. Jones,[153] S. Jones,[7] T. J. Jones,[88] J. Jongmanns,[59a] P. M. Jorge,[136a,136b] J. Jovicevic,[165a] X. Ju,[18] J. J. Junggeburth,[113] A. Juste Rozas,[14,w] A. Kaczmarska,[82] M. Kado,[128] H. Kagan,[122] M. Kagan,[150] T. Kaji,[176] E. Kajomovitz,[157] C. W. Kalderon,[94] A. Kaluza,[97] S. Kama,[41] A. Kamenshchikov,[140] L. Kanjir,[89] Y. Kano,[160] V. A. Kantserov,[110] J. Kanzaki,[79] B. Kaplan,[121] L. S. Kaplan,[178] D. Kar,[32c] M. J. Kareem,[165b] E. Karentzos,[10] S. N. Karpov,[77] Z. M. Karpova,[77] V. Kartvelishvili,[87] A. N. Karyukhin,[140] L. Kashif,[178] R. D. Kass,[122] A. Kastanas,[151] Y. Kataoka,[160] C. Kato,[58d,58c] J. Katzy,[44] K. Kawade,[80] K. Kawagoe,[85] T. Kawamoto,[160] G. Kawamura,[51] E. F. Kay,[88] V. F. Kazanin,[120b,120a] R. Keeler,[173] R. Kehoe,[41] J. S. Keller,[33] E. Kellermann,[94] J. J. Kempster,[21] J. Kendrick,[21] O. Kepka,[137] S. Kersten,[179] B. P. Kerševan,[89] R. A. Keyes,[101] M. Khader,[170] F. Khalil-Zada,[13] A. Khanov,[125] A. G. Kharlamov,[120b,120a] T. Kharlamova,[120b,120a] E. E. Khoda,[172] A. Khodinov,[163] T. J. Khoo,[52] E. Khramov,[77] J. Khubua,[156b] S. Kido,[80] M. Kiehn,[52] C. R. Kilby,[91] Y. K. Kim,[36] N. Kimura,[64a,64c] O. M. Kind,[19] B. T. King,[88] D. Kirchmeier,[46] J. Kirk,[141] A. E. Kiryunin,[113] T. Kishimoto,[160] D. Kisielewska,[81a] V. Kitali,[44] O. Kivernyk,[5] E. Kladiva,[28b] T. Klapdor-Kleingrothaus,[50] M. H. Klein,[103] M. Klein,[88] U. Klein,[88] K. Kleinknecht,[97] P. Klimek,[119] A. Klimentov,[29] R. Klingenberg,[45,a] T. Klingl,[24] T. Klioutchnikova,[35] F. F. Klitzner,[112] P. Kluit,[118] S. Kluth,[113] E. Kneringer,[74] E. B. F. G. Knoops,[99] A. Knue,[50] A. Kobayashi,[160] D. Kobayashi,[85] T. Kobayashi,[160] M. Kobel,[46] M. Kocian,[150] P. Kodys,[139] P. T. Koenig,[24] T. Koffas,[33] E. Koffeman,[118] N. M. Köhler,[113] T. Koi,[150] M. Kolb,[59b] I. Koletsou,[5] T. Kondo,[79] N. Kondrashova,[58c] K. Köneke,[50] A. C. König,[117] T. Kono,[79] R. Konoplich,[121,ff] V. Konstantinides,[92] N. Konstantinidis,[92] B. Konya,[94] R. Kopeliansky,[63] S. Koperny,[81a] K. Korcyl,[82] K. Kordas,[159] G. Koren,[158] A. Korn,[92] I. Korolkov,[14] E. V. Korolkova,[146] N. Korotkova,[111] O. Kortner,[113] S. Kortner,[113] T. Kosek,[139] V. V. Kostyukhin,[24] A. Kotwal,[47] A. Koulouris,[10]

A. Kourkoumeli-Charalampidi,[68a,68b] C. Kourkoumelis,[9] E. Kourlitis,[146] V. Kouskoura,[29] A. B. Kowalewska,[82] R. Kowalewski,[173] T. Z. Kowalski,[81a] C. Kozakai,[160] W. Kozanecki,[142] A. S. Kozhin,[140] V. A. Kramarenko,[111] G. Kramberger,[89] D. Krasnopevtsev,[58a] M. W. Krasny,[132] A. Krasznahorkay,[35] D. Krauss,[113] J. A. Kremer,[81a] J. Kretzschmar,[88] P. Krieger,[164] K. Krizka,[18] K. Kroeninger,[45] H. Kroha,[113] J. Kroll,[137] J. Kroll,[133] J. Krstic,[16] U. Kruchonak,[77] H. Krüger,[24] N. Krumnack,[76] M. C. Kruse,[47] T. Kubota,[102] S. Kuday,[4b] J. T. Kuechler,[179] S. Kuehn,[35] A. Kugel,[59a] F. Kuger,[174] T. Kuhl,[44] V. Kukhtin,[77] R. Kukla,[99] Y. Kulchitsky,[105] S. Kuleshov,[144b] Y. P. Kulinich,[170] M. Kuna,[56] T. Kunigo,[83] A. Kupco,[137] T. Kupfer,[45] O. Kuprash,[158] H. Kurashige,[80] L. L. Kurchaninov,[165a] Y. A. Kurochkin,[105] M. G. Kurth,[15d] E. S. Kuwertz,[35] M. Kuze,[162] J. Kvita,[126] T. Kwan,[101] A. La Rosa,[113] J. L. La Rosa Navarro,[78d] L. La Rotonda,[40b,40a] F. La Ruffa,[40b,40a] C. Lacasta,[171] F. Lacava,[70a,70b] J. Lacey,[44] D. P. J. Lack,[98] H. Lacker,[19] D. Lacour,[132] E. Ladygin,[77] R. Lafaye,[5] B. Laforge,[132] T. Lagouri,[32c] S. Lai,[51] S. Lammers,[63] W. Lampl,[7] E. Lançon,[29] U. Landgraf,[50] M. P. J. Landon,[90] M. C. Lanfermann,[52] V. S. Lang,[44] J. C. Lange,[14] R. J. Langenberg,[35] A. J. Lankford,[168] F. Lanni,[29] K. Lantzsch,[24] A. Lanza,[68a] A. Lapertosa,[53b,53a] S. Laplace,[132] J. F. Laporte,[142] T. Lari,[66a] F. Lasagni Manghi,[23b,23a] M. Lassnig,[35] T. S. Lau,[61a] A. Laudrain,[128] M. Lavorgna,[67a,67b] A. T. Law,[143] P. Laycock,[88] M. Lazzaroni,[66a,66b] B. Le,[102] O. Le Dortz,[132] E. Le Guirriec,[99] E. P. Le Quilleuc,[142] M. LeBlanc,[7] T. LeCompte,[6] F. Ledroit-Guillon,[56] C. A. Lee,[29] G. R. Lee,[144a] L. Lee,[57] S. C. Lee,[155] B. Lefebvre,[101] M. Lefebvre,[173] F. Legger,[112] C. Leggett,[18] K. Lehmann,[149] N. Lehmann,[179] G. Lehmann Miotto,[35] W. A. Leight,[44] A. Leisos,[159,gg] M. A. L. Leite,[78d] R. Leitner,[139] D. Lellouch,[177] B. Lemmer,[51] K. J. C. Leney,[92] T. Lenz,[24] B. Lenzi,[35] R. Leone,[7] S. Leone,[69a] C. Leonidopoulos,[48] G. Lerner,[153] C. Leroy,[107] R. Les,[164] A. A. J. Lesage,[142] C. G. Lester,[31] M. Levchenko,[134] J. Levêque,[5] D. Levin,[103] L. J. Levinson,[177] D. Lewis,[90] B. Li,[103] C-Q. Li,[58a] H. Li,[58b] L. Li,[58c] Q. Li,[15d] Q. Y. Li,[58a] S. Li,[58d,58c] X. Li,[58c] Y. Li,[148] Z. Liang,[15a] B. Liberti,[71a] A. Liblong,[164] K. Lie,[61c] S. Liem,[118] A. Limosani,[154] C. Y. Lin,[31] K. Lin,[104] T. H. Lin,[97] R. A. Linck,[63] J. H. Lindon,[21] B. E. Lindquist,[152] A. L. Lionti,[52] E. Lipeles,[133] A. Lipniacka,[17] M. Lisovyi,[59b] T. M. Liss,[170,hh] A. Lister,[172] A. M. Litke,[143] J. D. Little,[8] B. Liu,[76] B. L Liu,[6] H. B. Liu,[29] H. Liu,[103] J. B. Liu,[58a] J. K. K. Liu,[131] K. Liu,[132] M. Liu,[58a] P. Liu,[18] Y. Liu,[15a] Y. L. Liu,[58a] Y. W. Liu,[58a] M. Livan,[68a,68b] A. Lleres,[56] J. Llorente Merino,[15a] S. L. Lloyd,[90] C. Y. Lo,[61b] F. Lo Sterzo,[41] E. M. Lobodzinska,[44] P. Loch,[7] A. Loesle,[50] T. Lohse,[19] K. Lohwasser,[146] M. Lokajicek,[137] B. A. Long,[25] J. D. Long,[170] R. E. Long,[87] L. Longo,[65a,65b] K. A. Looper,[122] J. A. Lopez,[144b] I. Lopez Paz,[14] A. Lopez Solis,[146] J. Lorenz,[112] N. Lorenzo Martinez,[5] M. Losada,[22] P. J. Lösel,[112] X. Lou,[44] X. Lou,[15a] A. Lounis,[128] J. Love,[6] P. A. Love,[87] J. J. Lozano Bahilo,[171] H. Lu,[61a] M. Lu,[58a] N. Lu,[103] Y. J. Lu,[62] H. J. Lubatti,[145] C. Luci,[70a,70b] A. Lucotte,[56] C. Luedtke,[50] F. Luehring,[63] I. Luise,[132] L. Luminari,[70a] B. Lund-Jensen,[151] M. S. Lutz,[100] P. M. Luzi,[132] D. Lynn,[29] R. Lysak,[137] E. Lytken,[94] F. Lyu,[15a] V. Lyubushkin,[77] H. Ma,[29] L. L. Ma,[58b] Y. Ma,[58b] G. Maccarrone,[49] A. Macchiolo,[113] C. M. Macdonald,[146] J. Machado Miguens,[133,136b] D. Madaffari,[171] R. Madar,[37] W. F. Mader,[46] A. Madsen,[44] N. Madysa,[46] J. Maeda,[80] K. Maekawa,[160] S. Maeland,[17] T. Maeno,[29] A. S. Maevskiy,[111] V. Magerl,[50] C. Maidantchik,[78b] T. Maier,[112] A. Maio,[136a,136b,136d] O. Majersky,[28a] S. Majewski,[127] Y. Makida,[79] N. Makovec,[128] B. Malaescu,[132] Pa. Malecki,[82] V. P. Maleev,[134] F. Malek,[56] U. Mallik,[75] D. Malon,[6] C. Malone,[31] S. Maltezos,[10] S. Malyukov,[35] J. Mamuzic,[171] G. Mancini,[49] I. Mandić,[89] J. Maneira,[136a] L. Manhaes de Andrade Filho,[78a] J. Manjarres Ramos,[46] K. H. Mankinen,[94] A. Mann,[112] A. Manousos,[74] B. Mansoulie,[142] J. D. Mansour,[15a] M. Mantoani,[51] S. Manzoni,[66a,66b] G. Marceca,[30] L. March,[52] L. Marchese,[131] G. Marchiori,[132] M. Marcisovsky,[137] C. A. Marin Tobon,[35] M. Marjanovic,[37] D. E. Marley,[103] F. Marroquim,[78b] Z. Marshall,[18] M. U. F Martensson,[169] S. Marti-Garcia,[171] C. B. Martin,[122] T. A. Martin,[175] V. J. Martin,[48] B. Martin dit Latour,[17] M. Martinez,[14,w] V. I. Martinez Outschoorn,[100] S. Martin-Haugh,[141] V. S. Martoiu,[27b] A. C. Martyniuk,[92] A. Marzin,[35] L. Masetti,[97] T. Mashimo,[160] R. Mashinistov,[108] J. Masik,[98] A. L. Maslennikov,[120b,120a] L. H. Mason,[102] L. Massa,[71a,71b] P. Massarotti,[67a,67b] P. Mastrandrea,[5] A. Mastroberardino,[40b,40a] T. Masubuchi,[160] P. Mättig,[179] J. Maurer,[27b] B. Maček,[89] S. J. Maxfield,[88] D. A. Maximov,[120b,120a] R. Mazini,[155] I. Maznas,[159] S. M. Mazza,[143] N. C. Mc Fadden,[116] G. Mc Goldrick,[164] S. P. Mc Kee,[103] A. McCarn,[103] T. G. McCarthy,[113] L. I. McClymont,[92] E. F. McDonald,[102] J. A. Mcfayden,[35] G. Mchedlidze,[51] M. A. McKay,[41] K. D. McLean,[173] S. J. McMahon,[141] P. C. McNamara,[102] C. J. McNicol,[175] R. A. McPherson,[173,n] J. E. Mdhluli,[32c] Z. A. Meadows,[100] S. Meehan,[145] T. M. Megy,[50] S. Mehlhase,[112] A. Mehta,[88] T. Meideck,[56] B. Meirose,[42] D. Melini,[171,ii] B. R. Mellado Garcia,[32c] J. D. Mellenthin,[51] M. Melo,[28a] F. Meloni,[44] A. Melzer,[24] S. B. Menary,[98] E. D. Mendes Gouveia,[136a] L. Meng,[88] X. T. Meng,[103] A. Mengarelli,[23b,23a] S. Menke,[113] E. Meoni,[40b,40a] S. Mergelmeyer,[19] C. Merlassino,[20] P. Mermod,[52] L. Merola,[67a,67b] C. Meroni,[66a] F. S. Merritt,[36] A. Messina,[70a,70b] J. Metcalfe,[6] A. S. Mete,[168] C. Meyer,[133] J. Meyer,[157] J-P. Meyer,[142] H. Meyer Zu Theenhausen,[59a] F. Miano,[153] R. P. Middleton,[141] L. Mijović,[48]

G. Mikenberg,[177] M. Mikestikova,[137] M. Mikuž,[89] M. Milesi,[102] A. Milic,[164] D. A. Millar,[90] D. W. Miller,[36] A. Milov,[177] D. A. Milstead,[43a,43b] A. A. Minaenko,[140] M. Miñano Moya,[171] I. A. Minashvili,[156b] A. I. Mincer,[121] B. Mindur,[81a] M. Mineev,[77] Y. Minegishi,[160] Y. Ming,[178] L. M. Mir,[14] A. Mirto,[65a,65b] K. P. Mistry,[133] T. Mitani,[176] J. Mitrevski,[112] V. A. Mitsou,[171] A. Miucci,[20] P. S. Miyagawa,[146] A. Mizukami,[79] J. U. Mjörnmark,[94] T. Mkrtchyan,[181] M. Mlynarikova,[139] T. Moa,[43a,43b] K. Mochizuki,[107] P. Mogg,[50] S. Mohapatra,[38] S. Molander,[43a,43b] R. Moles-Valls,[24] M. C. Mondragon,[104] K. Mönig,[44] J. Monk,[39] E. Monnier,[99] A. Montalbano,[149] J. Montejo Berlingen,[35] F. Monticelli,[86] S. Monzani,[66a] N. Morange,[128] D. Moreno,[22] M. Moreno Llácer,[35] P. Morettini,[53b] M. Morgenstern,[118] S. Morgenstern,[46] D. Mori,[149] M. Morii,[57] M. Morinaga,[176] V. Morisbak,[130] A. K. Morley,[35] G. Mornacchi,[35] A. P. Morris,[92] J. D. Morris,[90] L. Morvaj,[152] P. Moschovakos,[10] M. Mosidze,[156b] H. J. Moss,[146] J. Moss,[150,jj] K. Motohashi,[162] R. Mount,[150] E. Mountricha,[35] E. J. W. Moyse,[100] S. Muanza,[99] F. Mueller,[113] J. Mueller,[135] R. S. P. Mueller,[112] D. Muenstermann,[87] G. A. Mullier,[20] F. J. Munoz Sanchez,[98] P. Murin,[28b] W. J. Murray,[175,141] A. Murrone,[66a,66b] M. Muškinja,[89] C. Mwewa,[32a] A. G. Myagkov,[140,kk] J. Myers,[127] M. Myska,[138] B. P. Nachman,[18] O. Nackenhorst,[45] K. Nagai,[131] K. Nagano,[79] Y. Nagasaka,[60] M. Nagel,[50] E. Nagy,[99] A. M. Nairz,[35] Y. Nakahama,[115] K. Nakamura,[79] T. Nakamura,[160] I. Nakano,[123] H. Nanjo,[129] F. Napolitano,[59a] R. F. Naranjo Garcia,[44] R. Narayan,[11] D. I. Narrias Villar,[59a] I. Naryshkin,[134] T. Naumann,[44] G. Navarro,[22] R. Nayyar,[7] H. A. Neal,[103] P. Y. Nechaeva,[108] T. J. Neep,[142] A. Negri,[68a,68b] M. Negrini,[23b] S. Nektarijevic,[117] C. Nellist,[51] M. E. Nelson,[131] S. Nemecek,[137] P. Nemethy,[121] M. Nessi,[35,ll] M. S. Neubauer,[170] M. Neumann,[179] P. R. Newman,[21] T. Y. Ng,[61c] Y. S. Ng,[19] H. D. N. Nguyen,[99] T. Nguyen Manh,[107] E. Nibigira,[37] R. B. Nickerson,[131] R. Nicolaidou,[142] J. Nielsen,[143] N. Nikiforou,[11] V. Nikolaenko,[140,kk] I. Nikolic-Audit,[132] K. Nikolopoulos,[21] P. Nilsson,[29] Y. Ninomiya,[79] A. Nisati,[70a] N. Nishu,[58c] R. Nisius,[113] I. Nitsche,[45] T. Nitta,[176] T. Nobe,[160] Y. Noguchi,[83] M. Nomachi,[129] I. Nomidis,[132] M. A. Nomura,[29] T. Nooney,[90] M. Nordberg,[35] N. Norjoharuddeen,[131] T. Novak,[89] O. Novgorodova,[46] R. Novotny,[138] L. Nozka,[126] K. Ntekas,[168] E. Nurse,[92] F. Nuti,[102] F. G. Oakham,[33,e] H. Oberlack,[113] T. Obermann,[24] J. Ocariz,[132] A. Ochi,[80] I. Ochoa,[38] J. P. Ochoa-Ricoux,[144a] K. O'Connor,[26] S. Oda,[85] S. Odaka,[79] S. Oerdek,[51] A. Oh,[98] S. H. Oh,[47] C. C. Ohm,[151] H. Oide,[53b,53a] M. L. Ojeda,[164] H. Okawa,[166] Y. Okazaki,[83] Y. Okumura,[160] T. Okuyama,[79] A. Olariu,[27b] L. F. Oleiro Seabra,[136a] S. A. Olivares Pino,[144a] D. Oliveira Damazio,[29] J. L. Oliver,[1] M. J. R. Olsson,[36] A. Olszewski,[82] J. Olszowska,[82] D. C. O'Neil,[149] A. Onofre,[136a,136e] K. Onogi,[115] P. U. E. Onyisi,[11] H. Oppen,[130] M. J. Oreglia,[36] Y. Oren,[158] D. Orestano,[72a,72b] E. C. Orgill,[98] N. Orlando,[61b] A. A. O'Rourke,[44] R. S. Orr,[164] B. Osculati,[53b,53a,a] V. O'Shea,[55] R. Ospanov,[58a] G. Otero y Garzon,[30] H. Otono,[85] M. Ouchrif,[34d] F. Ould-Saada,[130] A. Ouraou,[142] Q. Ouyang,[15a] M. Owen,[55] R. E. Owen,[21] V. E. Ozcan,[12c] N. Ozturk,[8] J. Pacalt,[126] H. A. Pacey,[31] K. Pachal,[149] A. Pacheco Pages,[14] L. Pacheco Rodriguez,[142] C. Padilla Aranda,[14] S. Pagan Griso,[18] M. Paganini,[180] G. Palacino,[63] S. Palazzo,[40b,40a] S. Palestini,[35] M. Palka,[81b] D. Pallin,[37] I. Panagoulias,[10] C. E. Pandini,[35] J. G. Panduro Vazquez,[91] P. Pani,[35] G. Panizzo,[64a,64c] L. Paolozzi,[52] T. D. Papadopoulou,[10] K. Papageorgiou,[9,t] A. Paramonov,[6] D. Paredes Hernandez,[61b] S. R. Paredes Saenz,[131] B. Parida,[58c] A. J. Parker,[87] K. A. Parker,[44] M. A. Parker,[31] F. Parodi,[53b,53a] J. A. Parsons,[38] U. Parzefall,[50] V. R. Pascuzzi,[164] J. M. P. Pasner,[143] E. Pasqualucci,[70a] S. Passaggio,[53b] F. Pastore,[91] P. Pasuwan,[43a,43b] S. Pataraia,[97] J. R. Pater,[98] A. Pathak,[178,f] T. Pauly,[35] B. Pearson,[113] M. Pedersen,[130] L. Pedraza Diaz,[117] R. Pedro,[136a,136b] S. V. Peleganchuk,[120b,120a] O. Penc,[137] C. Peng,[15d] H. Peng,[58a] B. S. Peralva,[78a] M. M. Perego,[142] A. P. Pereira Peixoto,[136a] D. V. Perepelitsa,[29] F. Peri,[19] L. Perini,[66a,66b] H. Pernegger,[35] S. Perrella,[67a,67b] V. D. Peshekhonov,[77,a] K. Peters,[44] R. F. Y. Peters,[98] B. A. Petersen,[35] T. C. Petersen,[39] E. Petit,[56] A. Petridis,[1] C. Petridou,[159] P. Petroff,[128] M. Petrov,[131] F. Petrucci,[72a,72b] M. Pettee,[180] N. E. Pettersson,[100] A. Peyaud,[142] R. Pezoa,[144b] T. Pham,[102] F. H. Phillips,[104] P. W. Phillips,[141] G. Piacquadio,[152] E. Pianori,[18] A. Picazio,[100] M. A. Pickering,[131] R. H. Pickles,[98] R. Piegaia,[30] J. E. Pilcher,[36] A. D. Pilkington,[98] M. Pinamonti,[71a,71b] J. L. Pinfold,[3] M. Pitt,[177] M-A. Pleier,[29] V. Pleskot,[139] E. Plotnikova,[77] D. Pluth,[76] P. Podberezko,[120b,120a] R. Poettgen,[94] R. Poggi,[52] L. Poggioli,[128] I. Pogrebnyak,[104] D. Pohl,[24] I. Pokharel,[51] G. Polesello,[68a] A. Poley,[18] A. Policicchio,[70a,70b] R. Polifka,[35] A. Polini,[23b] C. S. Pollard,[44] V. Polychronakos,[29] D. Ponomarenko,[110] L. Pontecorvo,[70a] G. A. Popeneciu,[27d] D. M. Portillo Quintero,[132] S. Pospisil,[138] K. Potamianos,[44] I. N. Potrap,[77] C. J. Potter,[31] H. Potti,[11] T. Poulsen,[94] J. Poveda,[35] T. D. Powell,[146] M. E. Pozo Astigarraga,[35] P. Pralavorio,[99] S. Prell,[76] D. Price,[98] M. Primavera,[65a] S. Prince,[101] N. Proklova,[110] K. Prokofiev,[61c] F. Prokoshin,[144b] S. Protopopescu,[29] J. Proudfoot,[6] M. Przybycien,[81a] A. Puri,[170] P. Puzo,[128] J. Qian,[103] Y. Qin,[98] A. Quadt,[51] M. Queitsch-Maitland,[44] A. Qureshi,[1] P. Rados,[102] F. Ragusa,[66a,66b] G. Rahal,[95] J. A. Raine,[52] S. Rajagopalan,[29] A. Ramirez Morales,[90] T. Rashid,[128] S. Raspopov,[5] M. G. Ratti,[66a,66b] D. M. Rauch,[44] F. Rauscher,[112] S. Rave,[97] B. Ravina,[146] I. Ravinovich,[177] J. H. Rawling,[98] M. Raymond,[35] A. L. Read,[130] N. P. Readioff,[56] M. Reale,[65a,65b] D. M. Rebuzzi,[68a,68b] A. Redelbach,[174] G. Redlinger,[29] R. Reece,[143]

R. G. Reed,[32c] K. Reeves,[42] L. Rehnisch,[19] J. Reichert,[133] A. Reiss,[97] C. Rembser,[35] H. Ren,[15d] M. Rescigno,[70a] S. Resconi,[66a] E. D. Resseguie,[133] S. Rettie,[172] E. Reynolds,[21] O. L. Rezanova,[120b,120a] P. Reznicek,[139] E. Ricci,[73a,73b] R. Richter,[113] S. Richter,[92] E. Richter-Was,[81b] O. Ricken,[24] M. Ridel,[132] P. Rieck,[113] C. J. Riegel,[179] O. Rifki,[44] M. Rijssenbeek,[152] A. Rimoldi,[68a,68b] M. Rimoldi,[20] L. Rinaldi,[23b] G. Ripellino,[151] B. Ristić,[87] E. Ritsch,[35] I. Riu,[14] J. C. Rivera Vergara,[144a] F. Rizatdinova,[125] E. Rizvi,[90] C. Rizzi,[14] R. T. Roberts,[98] S. H. Robertson,[101,n] D. Robinson,[31] J. E. M. Robinson,[44] A. Robson,[55] E. Rocco,[97] C. Roda,[69a,69b] Y. Rodina,[99] S. Rodriguez Bosca,[171] A. Rodriguez Perez,[14] D. Rodriguez Rodriguez,[171] A. M. Rodríguez Vera,[165b] S. Roe,[35] C. S. Rogan,[57] O. Røhne,[130] R. Röhrig,[113] C. P. A. Roland,[63] J. Roloff,[57] A. Romaniouk,[110] M. Romano,[23b,23a] N. Rompotis,[88] M. Ronzani,[121] L. Roos,[132] S. Rosati,[70a] K. Rosbach,[50] P. Rose,[143] N-A. Rosien,[51] E. Rossi,[44] E. Rossi,[67a,67b] L. P. Rossi,[53b] L. Rossini,[66a,66b] J. H. N. Rosten,[31] R. Rosten,[14] M. Rotaru,[27b] J. Rothberg,[145] D. Rousseau,[128] D. Roy,[32c] A. Rozanov,[99] Y. Rozen,[157] X. Ruan,[32c] F. Rubbo,[150] F. Rühr,[50] A. Ruiz-Martinez,[171] Z. Rurikova,[50] N. A. Rusakovich,[77] H. L. Russell,[101] J. P. Rutherfoord,[7] E. M. Rüttinger,[44,mm] Y. F. Ryabov,[134] M. Rybar,[170] G. Rybkin,[128] S. Ryu,[6] A. Ryzhov,[140] G. F. Rzehorz,[51] P. Sabatini,[51] G. Sabato,[118] S. Sacerdoti,[128] H. F-W. Sadrozinski,[143] R. Sadykov,[77] F. Safai Tehrani,[70a] P. Saha,[119] M. Sahinsoy,[59a] A. Sahu,[179] M. Saimpert,[44] M. Saito,[160] T. Saito,[160] H. Sakamoto,[160] A. Sakharov,[121,ff] D. Salamani,[52] G. Salamanna,[72a,72b] J. E. Salazar Loyola,[144b] D. Salek,[118] P. H. Sales De Bruin,[169] D. Salihagic,[113] A. Salnikov,[150] J. Salt,[171] D. Salvatore,[40b,40a] F. Salvatore,[153] A. Salvucci,[61a,61b,61c] A. Salzburger,[35] J. Samarati,[35] D. Sammel,[50] D. Sampsonidis,[159] D. Sampsonidou,[159] J. Sánchez,[171] A. Sanchez Pineda,[64a,64c] H. Sandaker,[130] C. O. Sander,[44] M. Sandhoff,[179] C. Sandoval,[22] D. P. C. Sankey,[141] M. Sannino,[53b,53a] Y. Sano,[115] A. Sansoni,[49] C. Santoni,[37] H. Santos,[136a] I. Santoyo Castillo,[153] A. Santra,[171] A. Sapronov,[77] J. G. Saraiva,[136a,136d] O. Sasaki,[79] K. Sato,[166] E. Sauvan,[5] P. Savard,[164,e] N. Savic,[113] R. Sawada,[160] C. Sawyer,[141] L. Sawyer,[93,v] C. Sbarra,[23b] A. Sbrizzi,[23b,23a] T. Scanlon,[92] J. Schaarschmidt,[145] P. Schacht,[113] B. M. Schachtner,[112] D. Schaefer,[36] L. Schaefer,[133] J. Schaeffer,[97] S. Schaepe,[35] U. Schäfer,[97] A. C. Schaffer,[128] D. Schaile,[112] R. D. Schamberger,[152] N. Scharmberg,[98] V. A. Schegelsky,[134] D. Scheirich,[139] F. Schenck,[19] M. Schernau,[168] C. Schiavi,[53b,53a] S. Schier,[143] L. K. Schildgen,[24] Z. M. Schillaci,[26] E. J. Schioppa,[35] M. Schioppa,[40b,40a] K. E. Schleicher,[50] S. Schlenker,[35] K. R. Schmidt-Sommerfeld,[113] K. Schmieden,[35] C. Schmitt,[97] S. Schmitt,[44] S. Schmitz,[97] J. C. Schmoeckel,[44] U. Schnoor,[50] L. Schoeffel,[142] A. Schoening,[59b] E. Schopf,[24] M. Schott,[97] J. F. P. Schouwenberg,[117] J. Schovancova,[35] S. Schramm,[52] A. Schulte,[97] H-C. Schultz-Coulon,[59a] M. Schumacher,[50] B. A. Schumm,[143] Ph. Schune,[142] A. Schwartzman,[150] T. A. Schwarz,[103] H. Schweiger,[98] Ph. Schwemling,[142] R. Schwienhorst,[104] A. Sciandra,[24] G. Sciolla,[26] M. Scornajenghi,[40b,40a] F. Scuri,[69a] F. Scutti,[102] L. M. Scyboz,[113] J. Searcy,[103] C. D. Sebastiani,[70a,70b] P. Seema,[24] S. C. Seidel,[116] A. Seiden,[143] T. Seiss,[36] J. M. Seixas,[78b] G. Sekhniaidze,[67a] K. Sekhon,[103] S. J. Sekula,[41] N. Semprini-Cesari,[23b,23a] S. Sen,[47] S. Senkin,[37] C. Serfon,[130] L. Serin,[128] L. Serkin,[64a,64b] M. Sessa,[72a,72b] H. Severini,[124] F. Sforza,[167] A. Sfyrla,[52] E. Shabalina,[51] J. D. Shahinian,[143] N. W. Shaikh,[43a,43b] L. Y. Shan,[15a] R. Shang,[170] J. T. Shank,[25] M. Shapiro,[18] A. S. Sharma,[1] A. Sharma,[131] P. B. Shatalov,[109] K. Shaw,[153] S. M. Shaw,[98] A. Shcherbakova,[134] Y. Shen,[124] N. Sherafati,[33] A. D. Sherman,[25] P. Sherwood,[92] L. Shi,[155,nn] S. Shimizu,[79] C. O. Shimmin,[180] M. Shimojima,[114] I. P. J. Shipsey,[131] S. Shirabe,[85] M. Shiyakova,[77] J. Shlomi,[177] A. Shmeleva,[108] D. Shoaleh Saadi,[107] M. J. Shochet,[36] S. Shojaii,[102] D. R. Shope,[124] S. Shrestha,[122] E. Shulga,[110] P. Sicho,[137] A. M. Sickles,[170] P. E. Sidebo,[151] E. Sideras Haddad,[32c] O. Sidiropoulou,[35] A. Sidoti,[23b,23a] F. Siegert,[46] Dj. Sijacki,[16] J. Silva,[136a] M. Silva Jr.,[178] M. V. Silva Oliveira,[78a] S. B. Silverstein,[43a] L. Simic,[77] S. Simion,[128] E. Simioni,[97] M. Simon,[97] R. Simoniello,[97] P. Sinervo,[164] N. B. Sinev,[127] M. Sioli,[23b,23a] G. Siragusa,[174] I. Siral,[103] S. Yu. Sivoklokov,[111] J. Sjölin,[43a,43b] P. Skubic,[124] M. Slater,[21] T. Slavicek,[138] M. Slawinska,[82] K. Sliwa,[167] R. Slovak,[139] V. Smakhtin,[177] B. H. Smart,[5] J. Smiesko,[28a] N. Smirnov,[110] S. Yu. Smirnov,[110] Y. Smirnov,[110] L. N. Smirnova,[111] O. Smirnova,[94] J. W. Smith,[51] M. N. K. Smith,[38] M. Smizanska,[87] K. Smolek,[138] A. Smykiewicz,[82] A. A. Snesarev,[108] I. M. Snyder,[127] S. Snyder,[29] R. Sobie,[173,n] A. M. Soffa,[168] A. Soffer,[158] A. Søgaard,[48] D. A. Soh,[155] G. Sokhrannyi,[89] C. A. Solans Sanchez,[35] M. Solar,[138] E. Yu. Soldatov,[110] U. Soldevila,[171] A. A. Solodkov,[140] A. Soloshenko,[77] O. V. Solovyanov,[140] V. Solovyev,[134] P. Sommer,[146] H. Son,[167] W. Song,[141] W. Y. Song,[165b] A. Sopczak,[138] F. Sopkova,[28b] D. Sosa,[59b] C. L. Sotiropoulou,[69a,69b] S. Sottocornola,[68a,68b] R. Soualah,[64a,64c,oo] A. M. Soukharev,[120b,120a] D. South,[44] B. C. Sowden,[91] S. Spagnolo,[65a,65b] M. Spalla,[113] M. Spangenberg,[175] F. Spanò,[91] D. Sperlich,[19] F. Spettel,[113] T. M. Spieker,[59a] R. Spighi,[23b] G. Spigo,[35] L. A. Spiller,[102] D. P. Spiteri,[55] M. Spousta,[139] A. Stabile,[66a,66b] R. Stamen,[59a] S. Stamm,[19] E. Stanecka,[82] R. W. Stanek,[6] C. Stanescu,[72a] B. Stanislaus,[131] M. M. Stanitzki,[44] B. Stapf,[118] S. Stapnes,[130] E. A. Starchenko,[140] G. H. Stark,[36] J. Stark,[56] S. H Stark,[39] P. Staroba,[137] P. Starovoitov,[59a] S. Stärz,[35] R. Staszewski,[82] M. Stegler,[44] P. Steinberg,[29] B. Stelzer,[149]

H. J. Stelzer,[35] O. Stelzer-Chilton,[165a] H. Stenzel,[54] T. J. Stevenson,[90] G. A. Stewart,[55] M. C. Stockton,[127] G. Stoicea,[27b] P. Stolte,[51] S. Stonjek,[113] A. Straessner,[46] J. Strandberg,[151] S. Strandberg,[43a,43b] M. Strauss,[124] P. Strizenec,[28b] R. Ströhmer,[174] D. M. Strom,[127] R. Stroynowski,[41] A. Strubig,[48] S. A. Stucci,[29] B. Stugu,[17] J. Stupak,[124] N. A. Styles,[44] D. Su,[150] J. Su,[135] S. Suchek,[59a] Y. Sugaya,[129] M. Suk,[138] V. V. Sulin,[108] D. M. S. Sultan,[52] S. Sultansoy,[4c] T. Sumida,[83] S. Sun,[103] X. Sun,[3] K. Suruliz,[153] C. J. E. Suster,[154] M. R. Sutton,[153] S. Suzuki,[79] M. Svatos,[137] M. Swiatlowski,[36] S. P. Swift,[2] A. Sydorenko,[97] I. Sykora,[28a] T. Sykora,[139] D. Ta,[97] K. Tackmann,[44,pp] J. Taenzer,[158] A. Taffard,[168] R. Tafirout,[165a] E. Tahirovic,[90] N. Taiblum,[158] H. Takai,[29] R. Takashima,[84] E. H. Takasugi,[113] K. Takeda,[80] T. Takeshita,[147] Y. Takubo,[79] M. Talby,[99] A. A. Talyshev,[120b,120a] J. Tanaka,[160] M. Tanaka,[162] R. Tanaka,[128] B. B. Tannenwald,[122] S. Tapia Araya,[144b] S. Tapprogge,[97] A. Tarek Abouelfadl Mohamed,[132] S. Tarem,[157] G. Tarna,[27b,q] G. F. Tartarelli,[66a] P. Tas,[139] M. Tasevsky,[137] T. Tashiro,[83] E. Tassi,[40b,40a] A. Tavares Delgado,[136a,136b] Y. Tayalati,[34e] A. C. Taylor,[116] A. J. Taylor,[48] G. N. Taylor,[102] P. T. E. Taylor,[102] W. Taylor,[165b] A. S. Tee,[87] P. Teixeira-Dias,[91] H. Ten Kate,[35] P. K. Teng,[155] J. J. Teoh,[118] F. Tepel,[179] S. Terada,[79] K. Terashi,[160] J. Terron,[96] S. Terzo,[14] M. Testa,[49] R. J. Teuscher,[164,n] S. J. Thais,[180] T. Theveneaux-Pelzer,[44] F. Thiele,[39] D. W. Thomas,[91] J. P. Thomas,[21] A. S. Thompson,[55] P. D. Thompson,[21] L. A. Thomsen,[180] E. Thomson,[133] Y. Tian,[38] R. E. Ticse Torres,[51] V. O. Tikhomirov,[108,qq] Yu. A. Tikhonov,[120b,120a] S. Timoshenko,[110] P. Tipton,[180] S. Tisserant,[99] K. Todome,[162] S. Todorova-Nova,[5] S. Todt,[46] J. Tojo,[85] S. Tokár,[28a] K. Tokushuku,[79] E. Tolley,[122] K. G. Tomiwa,[32c] M. Tomoto,[115] L. Tompkins,[150,ee] K. Toms,[116] B. Tong,[57] P. Tornambe,[50] E. Torrence,[127] H. Torres,[46] E. Torró Pastor,[145] C. Tosciri,[131] J. Toth,[99,rr] F. Touchard,[99] D. R. Tovey,[146] C. J. Treado,[121] T. Trefzger,[174] F. Tresoldi,[153] A. Tricoli,[29] I. M. Trigger,[165a] S. Trincaz-Duvoid,[132] M. F. Tripiana,[14] W. Trischuk,[164] B. Trocmé,[56] A. Trofymov,[128] C. Troncon,[66a] M. Trovatelli,[173] F. Trovato,[153] L. Truong,[32b] M. Trzebinski,[82] A. Trzupek,[82] F. Tsai,[44] J. C-L. Tseng,[131] P. V. Tsiareshka,[105] A. Tsirigotis,[159] N. Tsirintanis,[9] V. Tsiskaridze,[152] E. G. Tskhadadze,[156a] I. I. Tsukerman,[109] V. Tsulaia,[18] S. Tsuno,[79] D. Tsybychev,[152,163] Y. Tu,[61b] A. Tudorache,[27b] V. Tudorache,[27b] T. T. Tulbure,[27a] A. N. Tuna,[57] S. Turchikhin,[77] D. Turgeman,[177] I. Turk Cakir,[4b,ss] R. Turra,[66a] P. M. Tuts,[38] E. Tzovara,[97] G. Ucchielli,[23b,23a] I. Ueda,[79] M. Ughetto,[43a,43b] F. Ukegawa,[166] G. Unal,[35] A. Undrus,[29] G. Unel,[168] F. C. Ungaro,[102] Y. Unno,[79] K. Uno,[160] J. Urban,[28b] P. Urquijo,[102] P. Urrejola,[97] G. Usai,[8] J. Usui,[79] L. Vacavant,[99] V. Vacek,[138] B. Vachon,[101] K. O. H. Vadla,[130] A. Vaidya,[92] C. Valderanis,[112] E. Valdes Santurio,[43a,43b] M. Valente,[52] S. Valentinetti,[23b,23a] A. Valero,[171] L. Valéry,[44] R. A. Vallance,[21] A. Vallier,[5] J. A. Valls Ferrer,[171] T. R. Van Daalen,[14] H. Van der Graaf,[118] P. Van Gemmeren,[6] J. Van Nieuwkoop,[149] I. Van Vulpen,[118] M. Vanadia,[71a,71b] W. Vandelli,[35] A. Vaniachine,[163] P. Vankov,[118] R. Vari,[70a] E. W. Varnes,[7] C. Varni,[53b,53a] T. Varol,[41] D. Varouchas,[128] K. E. Varvell,[154] G. A. Vasquez,[144b] J. G. Vasquez,[180] F. Vazeille,[37] D. Vazquez Furelos,[14] T. Vazquez Schroeder,[101] J. Veatch,[51] V. Vecchio,[72a,72b] L. M. Veloce,[164] F. Veloso,[136a,136c] S. Veneziano,[70a] A. Ventura,[65a,65b] M. Venturi,[173] N. Venturi,[35] V. Vercesi,[68a] M. Verducci,[72a,72b] C. M. Vergel Infante,[76] C. Vergis,[24] W. Verkerke,[118] A. T. Vermeulen,[118] J. C. Vermeulen,[118] M. C. Vetterli,[149,e] N. Viaux Maira,[144b] M. Vicente Barreto Pinto,[52] I. Vichou,[170,a] T. Vickey,[146] O. E. Vickey Boeriu,[146] G. H. A. Viehhauser,[131] S. Viel,[18] L. Vigani,[131] M. Villa,[23b,23a] M. Villaplana Perez,[66a,66b] E. Vilucchi,[49] M. G. Vincter,[33] V. B. Vinogradov,[77] A. Vishwakarma,[44] C. Vittori,[23b,23a] I. Vivarelli,[153] S. Vlachos,[10] M. Vogel,[179] P. Vokac,[138] G. Volpi,[14] S. E. von Buddenbrock,[32c] E. Von Toerne,[24] V. Vorobel,[139] K. Vorobev,[110] M. Vos,[171] J. H. Vossebeld,[88] N. Vranjes,[16] M. Vranjes Milosavljevic,[16] V. Vrba,[138] M. Vreeswijk,[118] T. Šfiligoj,[89] R. Vuillermet,[35] I. Vukotic,[36] T. Ženiš,[28a] L. Živković,[16] P. Wagner,[24] W. Wagner,[179] J. Wagner-Kuhr,[112] H. Wahlberg,[86] S. Wahrmund,[46] K. Wakamiya,[80] V. M. Walbrecht,[113] J. Walder,[87] R. Walker,[112] S. D. Walker,[91] W. Walkowiak,[148] V. Wallangen,[43a,43b] A. M. Wang,[57] C. Wang,[58b,q] F. Wang,[178] H. Wang,[18] H. Wang,[3] J. Wang,[154] J. Wang,[59b] P. Wang,[41] Q. Wang,[124] R.-J. Wang,[132] R. Wang,[58a] R. Wang,[6] S. M. Wang,[155] W. T. Wang,[58a] W. Wang,[15c,tt] W. X. Wang,[58a,tt] Y. Wang,[58a] Z. Wang,[58c] C. Wanotayaroj,[44] A. Warburton,[101] C. P. Ward,[31] D. R. Wardrope,[92] A. Washbrook,[48] P. M. Watkins,[21] A. T. Watson,[21] M. F. Watson,[21] G. Watts,[145] S. Watts,[98] B. M. Waugh,[92] A. F. Webb,[11] S. Webb,[97] C. Weber,[180] M. S. Weber,[20] S. A. Weber,[33] S. M. Weber,[59a] A. R. Weidberg,[131] B. Weinert,[63] J. Weingarten,[51] M. Weirich,[97] C. Weiser,[50] P. S. Wells,[35] T. Wenaus,[29] T. Wengler,[35] S. Wenig,[35] N. Wermes,[24] M. D. Werner,[76] P. Werner,[35] M. Wessels,[59a] T. D. Weston,[20] K. Whalen,[127] N. L. Whallon,[145] A. M. Wharton,[87] A. S. White,[103] A. White,[8] M. J. White,[1] R. White,[144b] D. Whiteson,[168] B. W. Whitmore,[87] F. J. Wickens,[141] W. Wiedenmann,[178] M. Wielers,[141] C. Wiglesworth,[39] L. A. M. Wiik-Fuchs,[50] A. Wildauer,[113] F. Wilk,[98] H. G. Wilkens,[35] L. J. Wilkins,[91] H. H. Williams,[133] S. Williams,[31] C. Willis,[104] S. Willocq,[100] J. A. Wilson,[21] I. Wingerter-Seez,[5] E. Winkels,[153] F. Winklmeier,[127] O. J. Winston,[153] B. T. Winter,[24] M. Wittgen,[150] M. Wobisch,[93] A. Wolf,[97] T. M. H. Wolf,[118] R. Wolff,[99] M. W. Wolter,[82] H. Wolters,[136a,136c] V. W. S. Wong,[172] N. L. Woods,[143] S. D. Worm,[21] B. K. Wosiek,[82] K. W. Woźniak,[82] K. Wraight,[55] M. Wu,[36] S. L. Wu,[178]

X. Wu,[52] Y. Wu,[58a] T. R. Wyatt,[98] B. M. Wynne,[48] S. Xella,[39] Z. Xi,[103] L. Xia,[175] D. Xu,[15a] H. Xu,[58a] L. Xu,[29] T. Xu,[142] W. Xu,[103] B. Yabsley,[154] S. Yacoob,[32a] K. Yajima,[129] D. P. Yallup,[92] D. Yamaguchi,[162] Y. Yamaguchi,[162] A. Yamamoto,[79] T. Yamanaka,[160] F. Yamane,[80] M. Yamatani,[160] T. Yamazaki,[160] Y. Yamazaki,[80] Z. Yan,[25] H. J. Yang,[58c,58d] H. T. Yang,[18] S. Yang,[75] Y. Yang,[160] Z. Yang,[17] W-M. Yao,[18] Y. C. Yap,[44] Y. Yasu,[79] E. Yatsenko,[58c,58d] J. Ye,[41] S. Ye,[29] I. Yeletskikh,[77] E. Yigitbasi,[25] E. Yildirim,[97] K. Yorita,[176] K. Yoshihara,[133] C. J. S. Young,[35] C. Young,[150] J. Yu,[8] J. Yu,[76] X. Yue,[59a] S. P. Y. Yuen,[24] B. Zabinski,[82] G. Zacharis,[10] E. Zaffaroni,[52] R. Zaidan,[14] A. M. Zaitsev,[140,kk] T. Zakareishvili,[156b] N. Zakharchuk,[44] J. Zalieckas,[17] S. Zambito,[57] D. Zanzi,[35] D. R. Zaripovas,[55] S. V. Zeißner,[45] C. Zeitnitz,[179] G. Zemaityte,[131] J. C. Zeng,[170] Q. Zeng,[150] O. Zenin,[140] D. Zerwas,[128] M. Zgubič,[131] D. F. Zhang,[58b] D. Zhang,[103] F. Zhang,[178] G. Zhang,[58a] H. Zhang,[15c] J. Zhang,[6] L. Zhang,[15c] L. Zhang,[58a] M. Zhang,[170] P. Zhang,[15c] R. Zhang,[58a] R. Zhang,[24] X. Zhang,[58b] Y. Zhang,[15d] Z. Zhang,[128] X. Zhao,[41] Y. Zhao,[58b,128,y] Z. Zhao,[58a] A. Zhemchugov,[77] B. Zhou,[103] C. Zhou,[178] L. Zhou,[41] M. S. Zhou,[15d] M. Zhou,[152] N. Zhou,[58c] Y. Zhou,[7] C. G. Zhu,[58b] H. L. Zhu,[58a] H. Zhu,[15a] J. Zhu,[103] Y. Zhu,[58a] X. Zhuang,[15a] K. Zhukov,[108] V. Zhulanov,[120b,120a] A. Zibell,[174] D. Zieminska,[63] N. I. Zimine,[77] S. Zimmermann,[50] Z. Zinonos,[113] M. Zinser,[97] M. Ziolkowski,[148] G. Zobernig,[178] A. Zoccoli,[23b,23a] K. Zoch,[51] T. G. Zorbas,[146] R. Zou,[36] M. Zur Nedden,[19] and L. Zwalinski[35]

(ATLAS Collaboration)

[1]*Department of Physics, University of Adelaide, Adelaide, Australia*
[2]*Physics Department, SUNY Albany, Albany, New York, USA*
[3]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[4a]*Department of Physics, Ankara University, Ankara, Turkey*
[4b]*Istanbul Aydin University, Istanbul, Turkey*
[4c]*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
[5]*LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France*
[6]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*
[7]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[8]*Department of Physics, University of Texas at Arlington, Arlington, Texas, USA*
[9]*Physics Department, National and Kapodistrian University of Athens, Athens, Greece*
[10]*Physics Department, National Technical University of Athens, Zografou, Greece*
[11]*Department of Physics, University of Texas at Austin, Austin, Texas, USA*
[12a]*Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*
[12b]*Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*
[12c]*Department of Physics, Bogazici University, Istanbul, Turkey*
[12d]*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
[13]*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[14]*Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain*
[15a]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[15b]*Physics Department, Tsinghua University, Beijing, China*
[15c]*Department of Physics, Nanjing University, Nanjing, China*
[15d]*University of Chinese Academy of Science (UCAS), Beijing, China*
[16]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[17]*Department for Physics and Technology, University of Bergen, Bergen, Norway*
[18]*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA*
[19]*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
[20]*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[21]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[22]*Centro de Investigaciónes, Universidad Antonio Nariño, Bogota, Colombia*
[23a]*Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy*
[23b]*INFN Sezione di Bologna, Italy*
[24]*Physikalisches Institut, Universität Bonn, Bonn, Germany*
[25]*Department of Physics, Boston University, Boston, Massachusetts, USA*
[26]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[27a]*Transilvania University of Brasov, Brasov, Romania*
[27b]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[27c]*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*

[27d]National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
[27e]University Politehnica Bucharest, Bucharest, Romania
[27f]West University in Timisoara, Timisoara, Romania
[28a]Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
[28b]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[29]Physics Department, Brookhaven National Laboratory, Upton, New York, USA
[30]Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
[31]Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[32a]Department of Physics, University of Cape Town, Cape Town, South Africa
[32b]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
[32c]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[33]Department of Physics, Carleton University, Ottawa, Ontario, Canada
[34a]Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
[34b]Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN), Rabat, Morocco
[34c]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
[34d]Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
[34e]Faculté des sciences, Université Mohammed V, Rabat, Morocco
[35]CERN, Geneva, Switzerland
[36]Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
[37]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
[38]Nevis Laboratory, Columbia University, Irvington, New York, USA
[39]Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[40a]Dipartimento di Fisica, Università della Calabria, Rende, Italy
[40b]INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
[41]Physics Department, Southern Methodist University, Dallas, Texas, USA
[42]Physics Department, University of Texas at Dallas, Richardson, Texas, USA
[43a]Department of Physics, Stockholm University, Sweden
[43b]Oskar Klein Centre, Stockholm, Sweden
[44]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
[45]Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[46]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[47]Department of Physics, Duke University, Durham, North Carolina, USA
[48]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[49]INFN e Laboratori Nazionali di Frascati, Frascati, Italy
[50]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
[51]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
[52]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
[53a]Dipartimento di Fisica, Università di Genova, Genova, Italy
[53b]INFN Sezione di Genova, Italy
[54]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[55]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[56]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
[57]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
[58a]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
[58b]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
[58c]School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai, China
[58d]Tsung-Dao Lee Institute, Shanghai, China
[59a]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[59b]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[60]Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[61a]Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
[61b]Department of Physics, University of Hong Kong, Hong Kong, China
[61c]Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[62]Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
[63]Department of Physics, Indiana University, Bloomington, Indiana, USA

[64a]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
[64b]ICTP, Trieste, Italy
[64c]Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
[65a]INFN Sezione di Lecce, Italy
[65b]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[66a]INFN Sezione di Milano, Italy
[66b]Dipartimento di Fisica, Università di Milano, Milano, Italy
[67a]INFN Sezione di Napoli, Italy
[67b]Dipartimento di Fisica, Università di Napoli, Napoli, Italy
[68a]INFN Sezione di Pavia, Italy
[68b]Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[69a]INFN Sezione di Pisa, Italy
[69b]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[70a]INFN Sezione di Roma, Italy
[70b]Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[71a]INFN Sezione di Roma Tor Vergata, Italy
[71b]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[72a]INFN Sezione di Roma Tre, Italy
[72b]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
[73a]INFN-TIFPA, Italy
[73b]Università degli Studi di Trento, Trento, Italy
[74]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[75]University of Iowa, Iowa City, Iowa, USA
[76]Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
[77]Joint Institute for Nuclear Research, Dubna, Russia
[78a]Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
[78b]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
[78c]Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil
[78d]Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
[79]KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[80]Graduate School of Science, Kobe University, Kobe, Japan
[81a]AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
[81b]Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
[82]Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
[83]Faculty of Science, Kyoto University, Kyoto, Japan
[84]Kyoto University of Education, Kyoto, Japan
[85]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
[86]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[87]Physics Department, Lancaster University, Lancaster, United Kingdom
[88]Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[89]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
[90]School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[91]Department of Physics, Royal Holloway University of London, Egham, United Kingdom
[92]Department of Physics and Astronomy, University College London, London, United Kingdom
[93]Louisiana Tech University, Ruston, Louisiana, USA
[94]Fysiska institutionen, Lunds universitet, Lund, Sweden
[95]Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
[96]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
[97]Institut für Physik, Universität Mainz, Mainz, Germany
[98]School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[99]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
[100]Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
[101]Department of Physics, McGill University, Montreal, Québec, Canada
[102]School of Physics, University of Melbourne, Victoria, Australia
[103]Department of Physics, University of Michigan, Ann Arbor, Michigan, USA
[104]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
[105]B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
[106]Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
[107]Group of Particle Physics, University of Montreal, Montreal, Québec, Canada

[108]*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
[109]*Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
[110]*National Research Nuclear University MEPhI, Moscow, Russia*
[111]*D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
[112]*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
[113]*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
[114]*Nagasaki Institute of Applied Science, Nagasaki, Japan*
[115]*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
[116]*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
[117]*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
[118]*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
[119]*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
[120a]*Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*
[120b]*Novosibirsk State University Novosibirsk, Russia*
[121]*Department of Physics, New York University, New York, New York, USA*
[122]*Ohio State University, Columbus, Ohio, USA*
[123]*Faculty of Science, Okayama University, Okayama, Japan*
[124]*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
[125]*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
[126]*Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic*
[127]*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
[128]*LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
[129]*Graduate School of Science, Osaka University, Osaka, Japan*
[130]*Department of Physics, University of Oslo, Oslo, Norway*
[131]*Department of Physics, Oxford University, Oxford, United Kingdom*
[132]*LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*
[133]*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
[134]*Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg, Russia*
[135]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
[136a]*Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Portugal*
[136b]*Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
[136c]*Departamento de Física, Universidade de Coimbra, Coimbra, Portugal*
[136d]*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
[136e]*Departamento de Física, Universidade do Minho, Braga, Portugal*
[136f]*Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada (Spain), Spain*
[136g]*Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal*
[137]*Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[138]*Czech Technical University in Prague, Prague, Czech Republic*
[139]*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
[140]*State Research Center Institute for High Energy Physics, NRC KI, Protvino, Russia*
[141]*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
[142]*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[143]*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
[144a]*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
[144b]*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[145]*Department of Physics, University of Washington, Seattle, Washington, USA*
[146]*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
[147]*Department of Physics, Shinshu University, Nagano, Japan*
[148]*Department Physik, Universität Siegen, Siegen, Germany*
[149]*Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada*
[150]*SLAC National Accelerator Laboratory, Stanford, California, USA*
[151]*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
[152]*Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA*
[153]*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
[154]*School of Physics, University of Sydney, Sydney, Australia*
[155]*Institute of Physics, Academia Sinica, Taipei, Taiwan*
[156a]*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
[156b]*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
[157]*Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
[158]*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*

[159]*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[160]*International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
[161]*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
[162]*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
[163]*Tomsk State University, Tomsk, Russia*
[164]*Department of Physics, University of Toronto, Toronto, Ontario, Canada*
[165a]*TRIUMF, Vancouver, British Columbia, Canada*
[165b]*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
[166]*Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
[167]*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
[168]*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
[169]*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
[170]*Department of Physics, University of Illinois, Urbana, Illinois, USA*
[171]*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain*
[172]*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
[173]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*
[174]*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
[175]*Department of Physics, University of Warwick, Coventry, United Kingdom*
[176]*Waseda University, Tokyo, Japan*
[177]*Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel*
[178]*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
[179]*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
[180]*Department of Physics, Yale University, New Haven, Connecticut, USA*
[181]*Yerevan Physics Institute, Yerevan, Armenia*

[a]Deceased.
[b]Also at Department of Physics, King's College London, London, United Kingdom.
[c]Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.
[d]Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[e]Also at TRIUMF, Vancouver, British Columbia, Canada.
[f]Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.
[g]Also at Department of Physics, California State University, Fresno, California, USA.
[h]Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
[i]Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany.
[j]Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
[k]Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
[l]Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
[m]Also at Universita di Napoli Parthenope, Napoli, Italy.
[n]Also at Institute of Particle Physics (IPP), Canada.
[o]Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy.
[p]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
[q]Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
[r]Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[s]Also at Borough of Manhattan Community College, City University of New York, New York, USA.
[t]Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
[u]Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
[v]Also at Louisiana Tech University, Ruston, Louisiana, USA.
[w]Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[x]Also at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.
[y]Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
[z]Also at Graduate School of Science, Osaka University, Osaka, Japan.
[aa]Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
[bb]Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
[cc]Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
[dd]Also at CERN, Geneva, Switzerland.
[ee]Also at Department of Physics, Stanford University, USA.
[ff]Also at Manhattan College, New York, New York, USA.
[gg]Also at Hellenic Open University, Patras, Greece.

[hh]Also at The City College of New York, New York, New York, USA.
[ii]Also at Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada (Spain), Spain.
[jj]Also at Department of Physics, California State University, Sacramento, California, USA.
[kk]Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
[ll]Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
[mm]Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
[nn]Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
[oo]Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.
[pp]Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[qq]Also at National Research Nuclear University MEPhI, Moscow, Russia.
[rr]Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
[ss]Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
[tt]Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.